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SATELLITE-BASED EVIDENCE FOR URBAN AIR QUALITY POLICY: SPATIOTEMPORAL ASSESSMENT OF NITROGEN DIOXIDE USING COPERNICUS SENTINEL-5P

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Abstract
Air pollution has emerged as a major environmental and public health concern in rapidly expanding megacities. Nitrogen dioxide (NO_2), a key atmospheric pollutant primarily emitted from fossil fuel combustion, poses serious risks to human health and ecosystems. This study investigates the spatiotemporal variability of tropospheric NO_2 over Karachi, Pakistan, using Copernicus Sentinel-5P (TROPOMI) satellite observations from January 2019 to May 2025. Monthly, seasonal, and annual NO_2 distribution maps were generated using Geographic Information System (GIS) techniques to evaluate long-term trends and spatial patterns. The results reveal pronounced temporal variability in NO_2 concentrations, driven by meteorological conditions, COVID-19–related mobility restrictions, fluctuations in fuel prices, and industrial activities. A substantial decline in NO_2 levels was observed during lockdown periods, whereas elevated concentrations persisted during colder months, likely due to atmospheric stability and reduced pollutant dispersion. Overall, tropospheric NO_2 concentrations across Karachi consistently exceeded the World Health Organization (WHO) ambient air quality guidelines, indicating sustained population exposure to unhealthy air pollution levels. These findings underscore the critical role of satellite-based monitoring in urban air quality assessment and management. Integrating remote-sensing observations into regulatory frameworks can support policy evaluation, guide targeted emission-reduction strategies, and inform evidence-based decision-making aimed at improving air quality and protecting public health in megacities.

1. Introduction

The accelerated growth of the urban environment and industrialization of the whole developing world, along with the increased energy consumption, has resulted in the manifestation of a sharp drop in air quality, especially in the urban areas (Zhang et al., 2022). These processes have triggered the dramatic changes in peri-atmospheric composition, owing to complex interactions between physical, chemical, and biological processes, amplifying environmental degradation and worsening poor health effects on people (Saxena, 2025). Nitrogen dioxide (NO_2) is one of the most prominent representatives of the atmospheric pollutants, which holds a remarkable reputation in atmospheric chemistry and is largely undervalued in its potential degrading effect on human health (Saxena & Sonwani, 2019). The main contributors of NO_2 to an urban environment are high-temperature combustion processes, which are mostly caused by motor vehicle emissions, thermal power plants, and industrial activities (Piracha & Chaudhary, 2022). Epidemiological studies have continuously proven that long-term exposure to high levels of NO_2 is closely linked to respiratory illnesses, low lung capacity, and high rates of morbidity and mortality. The World Health Organization (WHO) claims that millions of premature deaths happen every year due to air pollution, and the poorest low- and middle-income nations bear the brunt of these consequences since urbanization usually exceeds environmental regulations and pollution prevention efforts (Baumgartner et al., 2020).

To address these issues, Earth observation technologies have turned out to be invaluable instruments for checking the pollutants in the atmosphere both within and outside the regional borders. The sensors on satellites offer spatially complete, temporally continuous datasets, which supplement and, in most areas, substitute the limited networks of air quality monitors on the ground (Holloway et al., 2021). The Sentinel-5P satellite, with the Tropospheric Monitoring Instrument (TROPOMI), is capable of providing high spatial resolution measurements of important trace gases, such as NO_2, and, therefore, can be used to make detailed measurements of the dynamic nature of urban air pollution and long-term variations (Reshi et al., 2024). The largest metropolitan government and economic centre of Pakistan (Figure 1), Karachi has always been one of the most contaminated cities in the world (Azhar et al., 2024). The worsening air quality in the city is motivated by a high level of traffic congestion, high concentration of industries, uncontrolled emissions, and a high rate of population growth, which puts a lot of pressure on the air quality in the urban setting. It is on this background that the current study will seek to measure the decadal-scale variability of tropospheric NO_2 in Karachi with Sentinel-5P and also understand the major dynamics that govern its time and space variations. Particularly, this study aims to track the changes in tropospheric NO_2 over Karachi based on Sentinel-5P remote sensing data; to determine the changes in monthly, seasonal, and annual spatial changes of NO_2 in 2019-2025; to determine the effects of meteorological factors, COVID-19 mobility restrictions, and economy on changes in NO_2; and to compare the measured concentrations with the WHO ambient air quality standards. Although there are environmental regulations in Pakistan, the fact that such regulations have been facing serious threats like a lack of enforcement, a lack of enough capacity to monitor, and a lack of strong integration of scientific evidence into policies, among others, has not been able to facilitate significant changes in air quality in the urban areas. It is against this backdrop that satellite-based evidence will provide a strong tool to contribute to the regulatory decision-making, assess policy effectiveness, and educate on the formulation of specific emission mitigation initiatives to manage sustainable urban air quality.

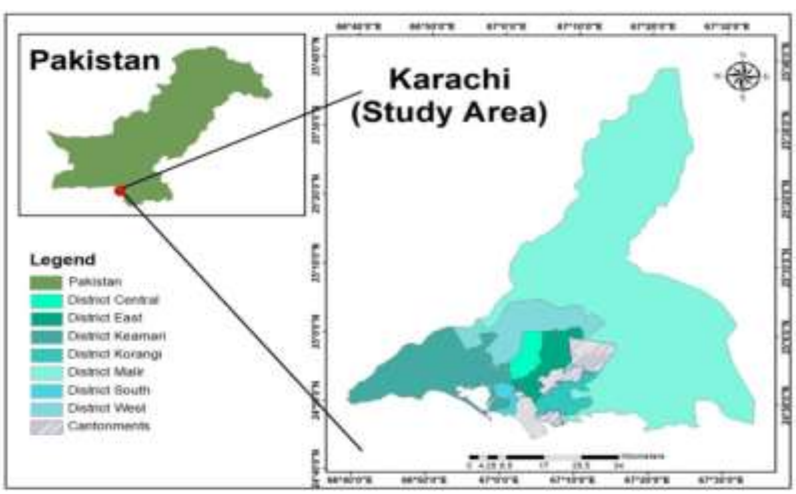

Figure 1. Location of study area, Karachi, Pakistan

Nitrogen dioxide is generally considered to be one of the major pollutants in urban settings, thus causing enormous threats to human health and ecology. Strong epidemiological data prove a definite dependence between exposure to respirator ambient NO_2 and the increase of respiratory morbidity and mortality (Chen et al., 2024). Moreover, high levels of NO_2 enhance the formation of secondary oxidized species (including ozone, nitric acid, and nitrates), which, in turn, increase the formation of smog and acid deposition. In Karachi, it is not possible to carry out an overall evaluation of NO_2 pollution due to the sparseness of ground-based monitoring stations. As a result, it is required that effective, large-scale monitoring networks are able to measure the concentration of NO_2 with high precision and monitor their time dynamics. Satellite remote sensing provides a viable remedy, which can help to bridge these information gaps and provide the empirical basis of air-quality regulation. The absence of air-quality information on a spatial scale is a setback to policy formulation, evaluation, and execution of effective emission-controlling policies.

3. Objectives

4. Literature Review

Air quality surveillance has become an important environmental issue in Karachi, a city that has remained among the destinations with the worst air quality indices in South Asia and the world at large (Mughal et al., 2015). In recent years, the situation has become more severe, and several Pakistani cities have made it to the top of the list of the most polluted by air regions across the world in consecutive versions of the World Air Quality Report. One of the most urgent environmental issues in Pakistan is the outcomes of the worsening air quality on population health and life expectancy (Azam et al., 2023). Empirical studies show that, due to air pollution in the air, average life expectancy in the country is reduced by about 3.9 years, with the health and productivity losses to which they are accompanied being a high economic cost, estimated at about a loss of somewhere between 6-9 per cent of the national GDP in a year. These results highlight the importance of strong, sustainable air-quality monitoring systems that can support evidence-based policy responses.

Nitrogen dioxide (NO_2) is one of the major atmospheric pollutants that has been identified as the second most harmful air pollutant in Pakistan after particulate matter. The levels of NO_2 in cities are often above the ambient air-quality standards established by the World Health Organization (WHO), and this is highly dangerous to human health, especially due to respiratory and cardiovascular effects (WHO, 2006). This is further complicated by the urban structure in Karachi and the nature of the sources of emissions. The city also accommodates a few big industrial complexes, such as the Korangi Industrial and Trading Estate, Sindh Industrial and Trading Estate (SITE), North Karachi Industrial and Trading Estate, Federal B Area, and Port Qasim, among which the contribution to the high levels of NO_2 emissions is significant (Idrees et al., 2023). The intensive development of the industrial world has significantly increased environmental pollution, and its effects have been observed to extend past the city limits to peri-urban and rural regions and therefore threaten ecosystems, which were once believed to be relatively clean (Idrees et al., 2023).

Besides industrial emissions, municipal and solid waste burning has also become a significant pollutant of urban air in Karachi, and it further increases the environmental degradation and threatens the population with significant health threats (Moyebi et al., 2023). The major sources of emissions are power generation plants, manufacturing industries, agricultural activities, domestic energy consumption, and a growing car fleet (Figure 2). Although the increasing awareness of these sources of emissions, ground-based pollution networks in Karachi have low spatial coverage and temporal continuity, which limit the possibility of wholesome measurements of NO_2 dynamics within the metropolitan.

The current understanding of satellite remote sensing has overcome these shortcomings by allowing large-scale monitoring of atmospheric pollutants in a consistent manner. The use of satellite-based NO_2 measures has been shown to be effective in measuring spatiotemporal variations as well as detecting emission hotspots and gauging the effects of policy changes and external shocks like economic fluctuations and mobility costs. Nevertheless, within the setting of Karachi, a significant gap in the long-term, high-resolution satellite-based measurement, which clearly links the observed trends in NO_2 to policy and regulatory decision-making in air quality, does exist. To address the gap, the current research paper is based on the available literature using the Sentinel-5P (TROPOMI) data to conduct an all-encompassing spatiotemporal analysis on tropospheric NO_2, which will inform policy-relevant evidence and manage air-quality sustainability in urban environments.

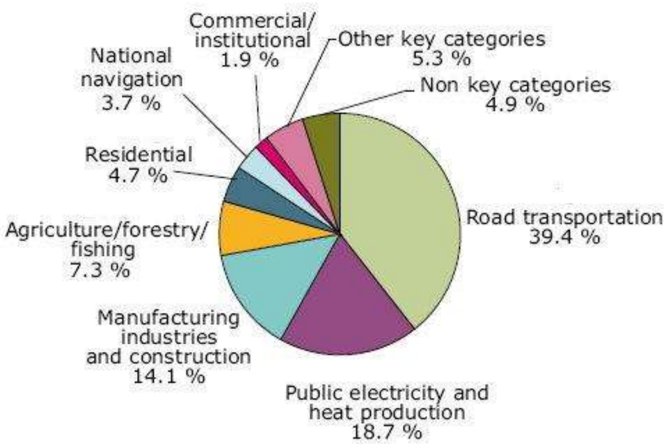

Figure 2. Sources of Nitrogen dioxide (NO_2) emission

5. Methodology

5.1 Data Acquisition

The Copernicus Sentinel 5P satellite, which has a Tropospheric Monitoring Instrument (TROPOMI), was used to obtain Nitrogen dioxide (NO_2) column density data in the troposphere. This data includes January 2019 to May 2025 and brings about trend analysis and policy evaluation suitable for long-term observations. Sentinel5P provides high spatial resolution and global coverage, which makes it especially suitable to track air pollution on an urban level. All the data of NO_2 were available freely through the Copernicus Open Access Hub in raster form. The datasets portray the tropospheric vertical column densities of NO_2 and were re-projected to the World Geodetic System 1984 (WGS-84) geospatial coordinate system so as to achieve spatial congruity with other geospatial data.

5.2 Data Processing and Spatial Analysis

The geospatial boundary datasets of Karachi were acquired and utilized as a spatial mask to obtain city-specific NO_2 values of the Sentinel 5P raster layers. This clip exercise ensures that analysis is done on the urban area of Karachi only. To reduce the impact of missing data and interim fluctuations, daily satellite measurements were averaged to get monthly mean NO_2 levels. These monthly datasets were thereafter summed up in order to form seasonal and annual composites, and therefore could assess intra-annual and inter-annual variability. The classification into seasons was subject to the climatic conditions of the region, which these seasons included winter, pre-monsoon, monsoon, and post-monsoon seasons. All geographical analyses have been done by the application of the Geographic Information System (GIS). Raster resampling, when required, was done to keep the spatial resolution of the raster resampled the same throughout the temporal dataset; therefore, it was able to compare NO_2 concentrations across time.

5.3 Analysis of Data and Trends

Tropospheric NO_2 spatial distribution maps were created monthly, seasonally, and annually in order to visualize the pattern of pollution in Karachi. The concentrations of NO_2 were grouped into various categories, which depended on the minimum and maximum concentrations that were observed, thus highlighting the spatial gradients and the hotspots of emissions. Descriptive statistical values such as mean, median, standard deviation, and coefficient of variation were used to assess the temporal trends. Annual and seasonal means of NO_2 were used to produce the graphical representations, which were used to analyze the long-term patterns and determine the impact of external factors on these measurements, including the meteorological conditions, COVID-19 mobility restrictions, and the economic fluctuations. The joint spatial-temporal analytical model offers a solid foundation to detect the trends of persistent pollution and evaluate the air quality policy in the urban environment with evidence-based criteria. Figure 3 shows a methodology flowchart.

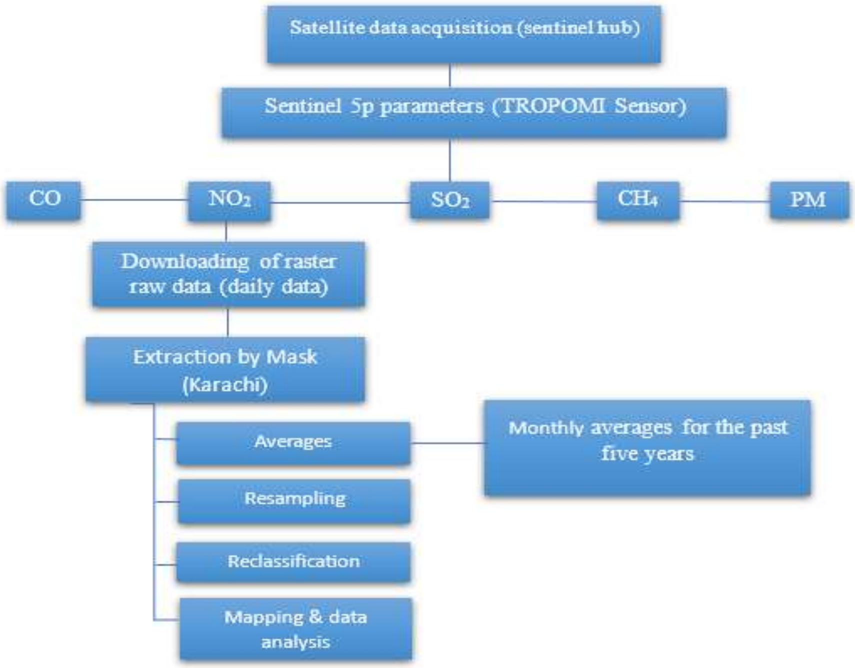

Figure 3. Dataset collection and methodology flowchart

6. Results and Discussion

Spatiotemporal pattern of NO_2 concentration in the troposphere in Karachi reveals that there is strong inter-annual and seasonal variation in tropospheric NO_2 patterns in Karachi during the period (Figures 4-8). Peak NO_2 levels are present in the winter season across all the years, and the tendency has always been attributed to reduced ambient temperatures, prevalent temperature inversion, and inhibited atmospheric mixing, which all favor the concentration of pollutants near the surface. Relatively low levels of NOx are witnessed in summer and monsoon periods, which are indicative of augmented vertical and horizontal diffusion attributable to augmented atmospheric instability, in addition to the moisture-eliminating impacts of rain. This seasonality is typical of the subtropical coastal megacities, and it has been extensively recorded in satellite-based urban air-quality measurements. It can be seen that the level of NO_2 has decreased significantly in 2019 and, more noticeably, in 2020 (Figures 4 and 5) because of the enactment of lockdown protocols due to COVID-19 that significantly reduced vehicular traffic, industrial operation, and business transactions. Such a sudden decrease shows how urban NO_2 levels are susceptible to the sources of anthropogenic emissions, especially in the transport and industrial sectors. After the lifting of lockdown restrictions, the following years record a slow rise in NO_2 levels, which is more or less a reflection of the re-establishment of economic activity and energy use in the metropolitan area. Nevertheless, this is not a linear and homogenous recovery, and this fact highlights the complexity of the interactions among emission sources, weather conditions, and socio-economic factors.

Figure 7 shows that in 2022, there is an unusual decline in NO_2 emissions (Figure 7), which can be explained by the fact that the monsoon rains were remarkably heavy and contributed to the cleansing of the atmosphere due to wet deposition and suppressed the accumulation of pollutants in the air. In its turn, the spatial patterns of 2023 (Figure 8) are similar to the impact of macro-economic constraints, such as increasing fuel prices and decreased vehicle use, which led to the temporary decrease in traffic-related emissions (Kumbhar et al., 2025). The results indicate that, in addition to meteorological forcing, larger economic and policy-oriented processes have an observable impact on urban air-pollution processes, which adds to the usefulness of satellite observations in selecting such multifaceted processes. Although these temporary decreases are present, the levels of tropospheric NO_2 in Karachi always exceed the recommended levels of the annual guidelines of the World Health Organization (WHO), which means that the city population is constantly subjected to unhealthy air quality levels (Goshua et al., 2022). This enduring surpassing indicates how structural the air-pollution issue in Karachi is and how constrained short-term emissions are in reducing the air-pollution levels in the long term. The results of the annual descriptive statistics of troposphere NO_2 using Sentinel 5 P TROPOMI observations in the years 2019 and 2025 are presented in Table 1.

The findings verify high inter-annual variability, with 2019 (5.8 x 10 -5) and 2020 (3.9 x 10 -5) having the highest and lowest mean NO_2 concentration, respectively, when COVID-19 restrictions were at their peak. During the post-lockdown period, the level of NO_2 is slowly recovering, with year-to-year variation being due to a mixture of meteorological and socio-economic factors. The standard deviation and the coefficient of variation are high throughout the years, and this shows that the spatial heterogeneity in the city and the temporal variability in the concentrations of NO_2 are high. This variability is an indication of uneven distribution of the sources of emissions, such as traffic corridors, industry areas, and residential combustion, and also the meteorological localities. Altogether, the findings can serve as strong satellite-assisted pieces of evidence of the chronic problem of NO_2 pollution in Karachi, which consists of continuous violations of health-related standards despite temporary improvements due to external shocks connected to lockdowns, economic decline, and extreme weather conditions. Such results underscore the need to incorporate high-resolution satellite images in urban air-quality management systems. Sentinel -5P data provide an effective instrument for measuring the success of the policy, the places where emissions are concentrated, and the construction of specific mitigation strategies to be applied and promote lasting changes in NO_2 levels and enhance the quality of the human condition in the rapidly growing megalopolis.

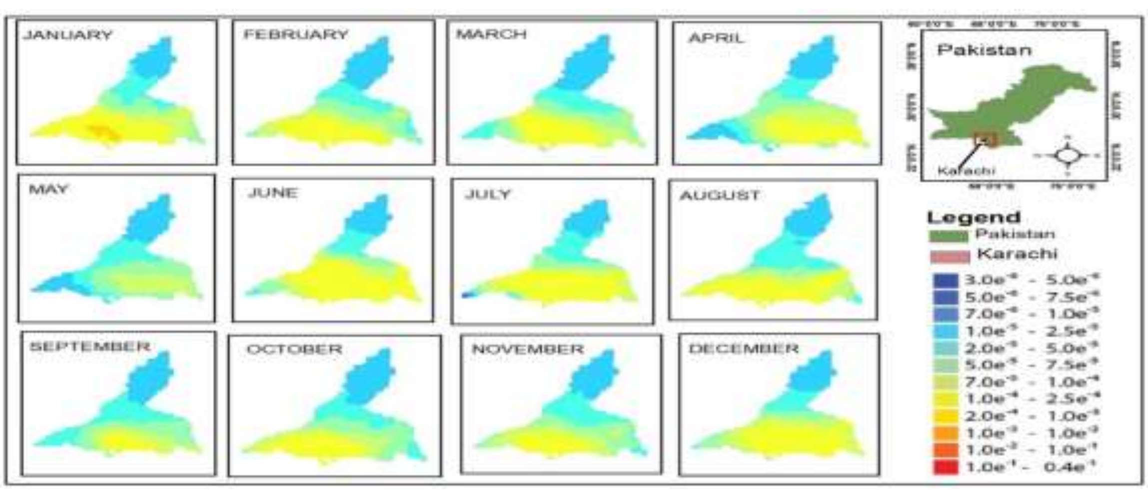

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Figure 4. Map of NO_2 concentration monthly for the year 2019.

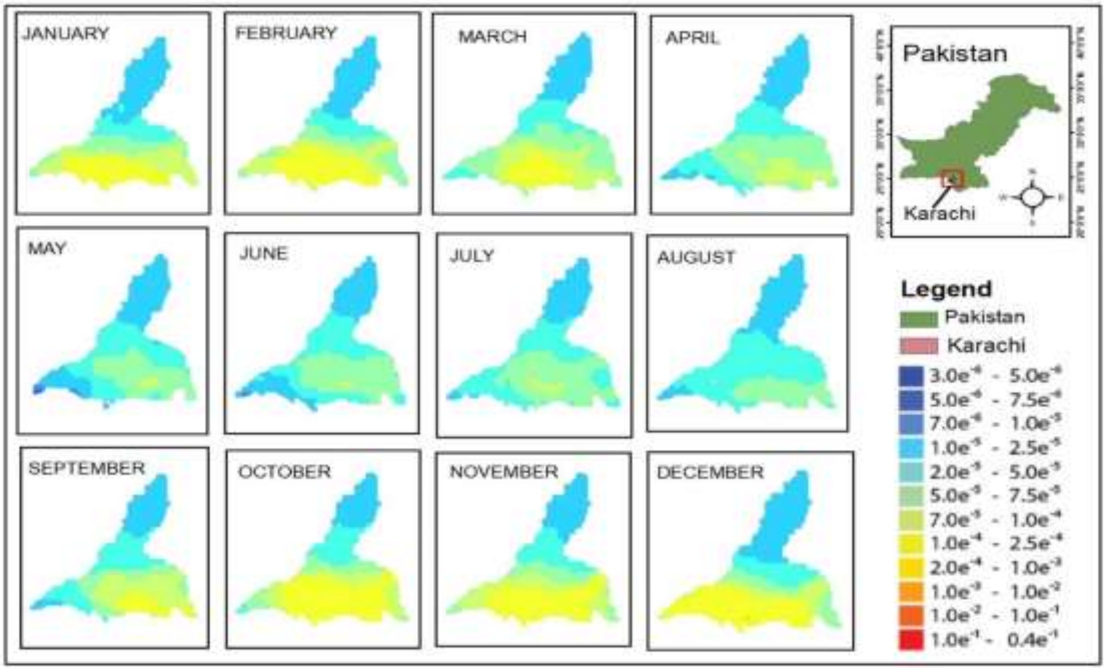

Figure 5. Map of NO_2 concentration monthly for the year 2021.

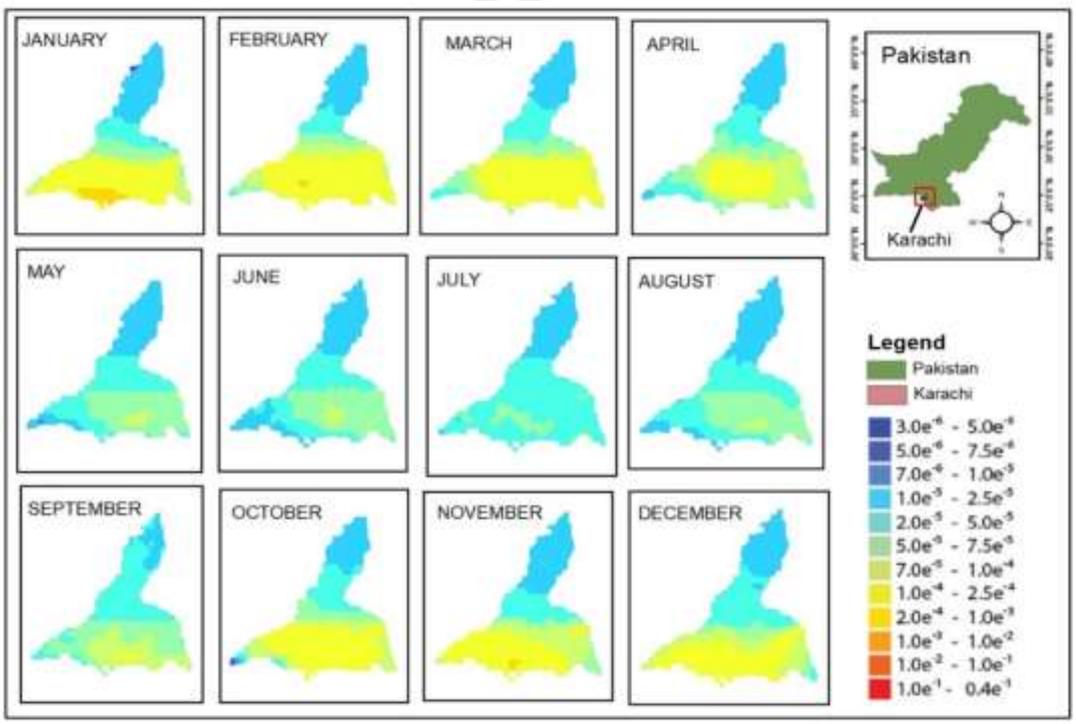

Figure 6. Map of NO_2 concentration monthly for the year 2022

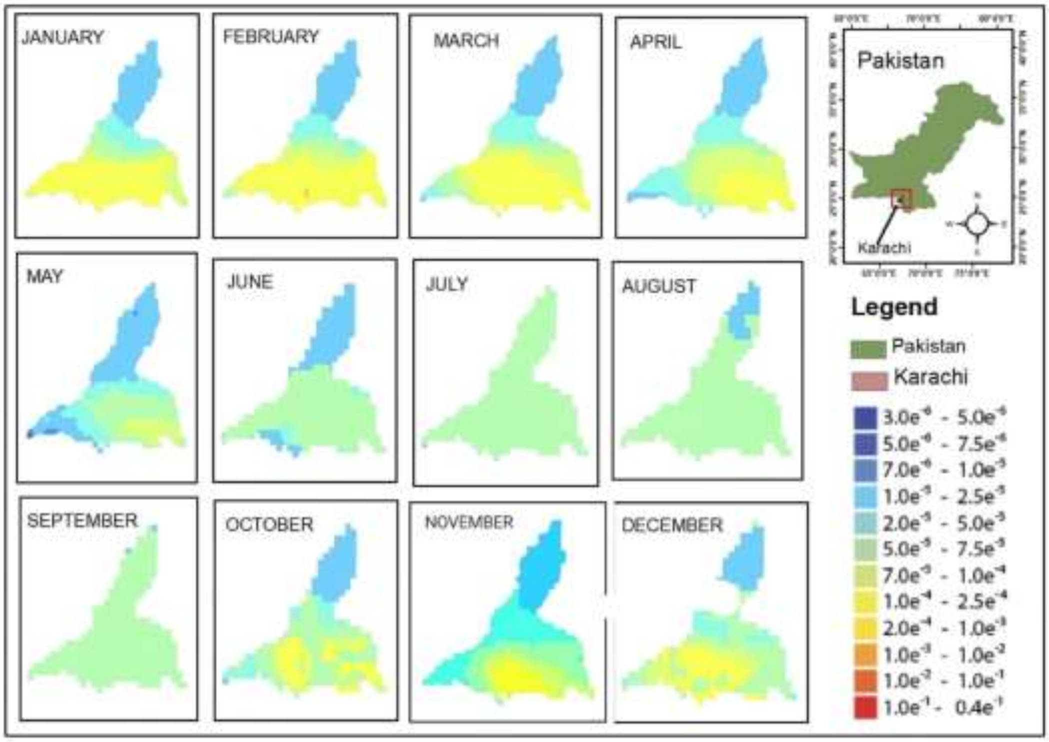

Figure 7. Map of NO_2 concentration monthly for the year 2023

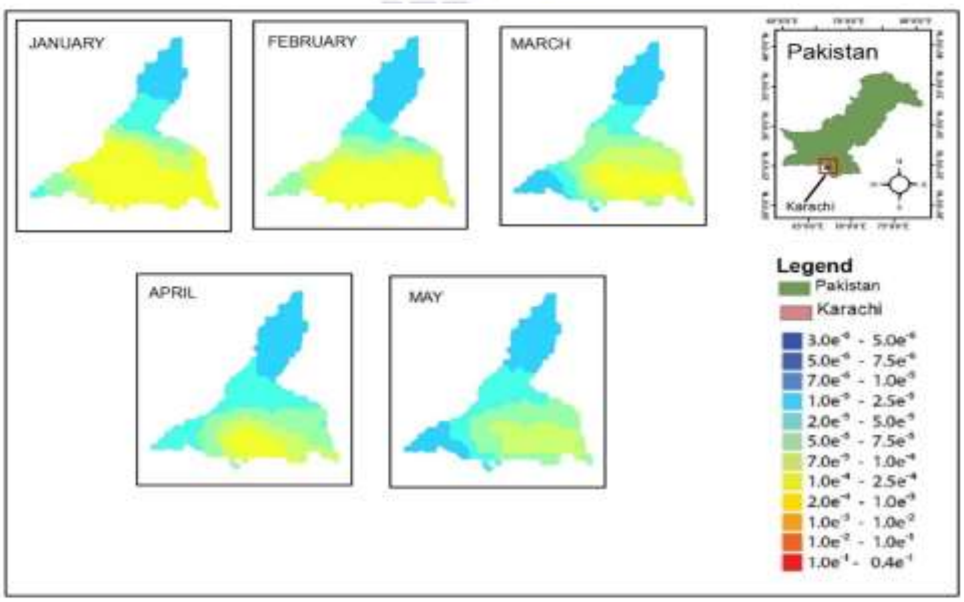

Figure 8. Map of NO_2 concentration monthly for the year 2025

Table 1. Annual descriptive statistics of tropospheric NO_2

Year	Mean NO_2	Median NO_2	Minimum	Maximum	Standard Deviation	Coefficient of Variation (%)
2019	5.8×10^{-5}	5.6×10^{-5}	2.1×10^{-5}	9.4×10^{-5}	1.9×10^{-5}	32.8
2020	3.9×10^{-5}	3.7×10^{-5}	1.6×10^{-5}	6.8×10^{-5}	1.2×10^{-5}	30.7

2021	5.2×10^{-5}	5.0×10^{-5}	2.0×10^{-5}	8.7×10^{-5}	1.7×10^{-5}	32.6
2022	4.7×10^{-5}	4.6×10^{-5}	1.8×10^{-5}	8.1×10^{-5}	1.5×10^{-5}	31.9
2023	4.3×10^{-5}	4.2×10^{-5}	1.7×10^{-5}	7.6×10^{-5}	1.4×10^{-5}	32.5
2024	4.9×10^{-5}	4.8×10^{-5}	1.9×10^{-5}	8.3×10^{-5}	1.6×10^{-5}	32.7
2025*	5.1×10^{-5}	5.0×10^{-5}	2.0×10^{-5}	8.5×10^{-5}	1.7×10^{-5}	33.3

7. Conclusion

This study shows that Copernicus Sentinel-5P -5P TROPOMI measurements are the strongest to monitor tropospheric nitrogen dioxide (NO_2) in Karachi over the period of 2019-2025, which provides satellite-based data that significantly supports policy-making in urban air quality. The inter-annual changes in NO_2 concentrations are revealed as significant, and the annual means of the levels vary between 3.9×10^{-5} mol m^{-2} in 2020 and about 5.8×10^{-5} mol m^{-2} in 2019, which highlights the major impact of human emissions and externally imposed interventions on the quality of the air in the city.

The strong reduction of almost 33 percent in 2020 compared with the pre-lockdown state offers quantitative support for the air-quality advantage that can be attributed to the COVID-19-related movement restrictions and industrial stagnation. The tropospheric NO_2 levels follow a slow but irregular pattern of resurgence in the post-lockdown period (2021-2025) with central values that vary between 4.3×10^{-5} and 5.1×10^{-5} mol m^{-2}. This trend indicates the synergies between economic reactivation, changes in fuel consumption, and inter-annual meteorological variability. Such significantly high standard deviations (1.2×10^{-5} to 1.9×10^{-5} mol m^{-2}) and coefficients of variation (30.7-33.3%) throughout all study years testify to the fact that spatial and temporal heterogeneity in the distribution of NO_2 remains very high and thus confirms that the sample remains imbued with localized hotspots of emissions along major traffic routes and industrial areas.

These results also emphasize the fact that increased NO_2 levels are still one of the enduring characteristics of the city environment in Karachi. Altogether, the results validate the hypothesis that the troposphere levels of NO_2 in Karachi are always above the air-quality standards suggested by international regulations, which indicates a systemic and ongoing air-pollution epidemic. At the same time, the fact that NO_2 concentrations were so sensitive to policy action, macro-economic shocks, and the limitation of mobility highlights how significant a reduction in emissions can be achieved by applied and well-planned control measures. Combining satellite-based observations and strict statistical analysis is a potent tool in the evaluation of urban air quality, especially in areas where there is a lack of ground-based monitoring infrastructure. To conclude, this study highlights how satellite-based observations of NO_2 are a key decision-support instrument in evidence-based environmental governance.

The inclusion of such data into the regulatory frameworks allows authorities to consider compliance better, estimate the effectiveness of interventions, and think of a long-term policy regarding emission reduction. The reinforcement of the public transport network, the encouragement of the use of cleaner energy sources and fuel, and the implementation of the control of industrial emissions are the key measures that can be taken to enhance the air quality and protect the population in Karachi. This paper reaffirms the importance of satellite-based evidence in developing sustainable urban air-quality controls of the fast-growing megacities.

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