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Spatiotemporal dynamics and drivers of air pollution in Pakistan: A national-scale multi-pollutant analysis.

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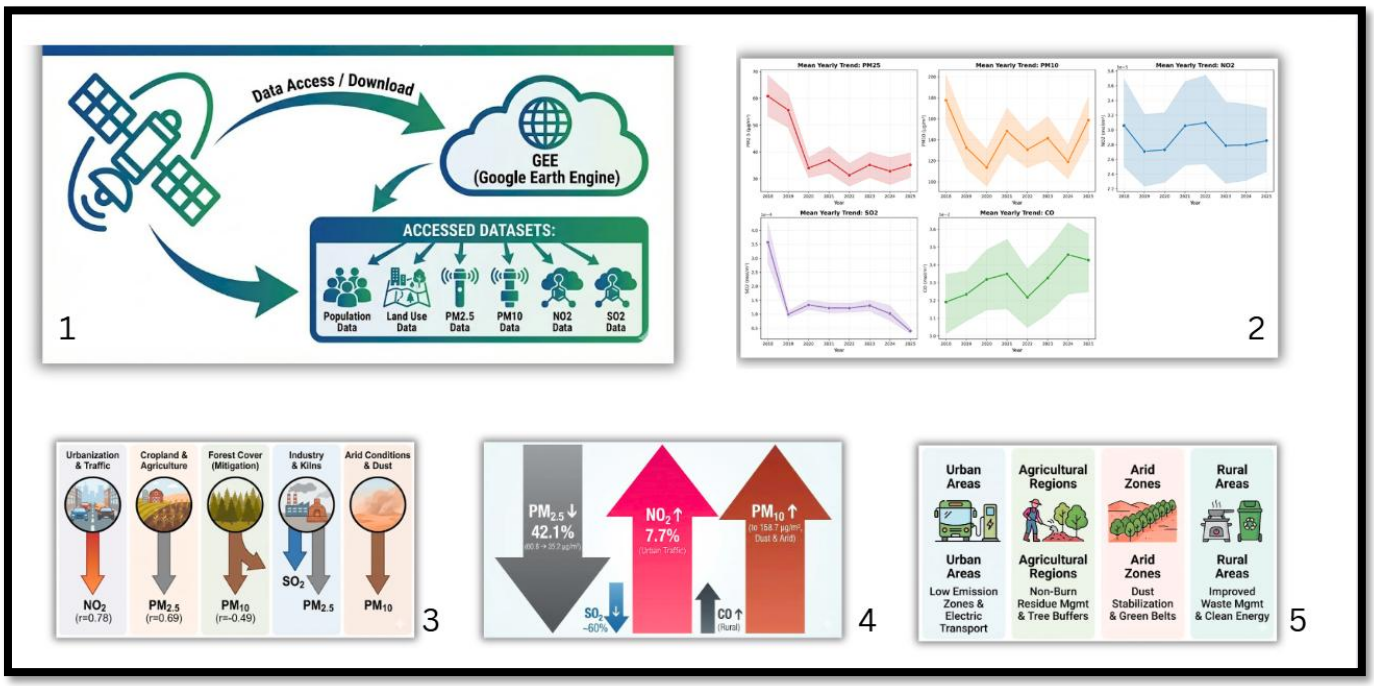
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Abstract

Air pollution is a major public health crisis in Pakistan, driven by rapid urbanization, industrial expansion, agricultural burning, and inadequate monitoring infrastructure. This study evaluates five major pollutants inlcuding PM2.5, PM10, NO2, SO2, and CO across all administrative divisions of Pakistan from 2018 to 2025 using multi-sensor satellite observations (Sentinel-5P TROPOMI, MODIS, MERRA-2, GHAP, CAMS) integrated with population and land-use data. This study presents the first national, division level multi pollutant analysis of Pakistan, explicitly decomposing the confounding effect of the COVID-19 lockdown 2020 to 2021 from long term emission trends. Nationwide PM2.5 concentrations declined by 42.1%, from 60.85 µg/m³ in 2018 to 35.20 µg/m³ in 2025. However, a sharp and temporary reduction was observed in 2020 coinciding with COVID-19 lockdowns; after accounting for this disruption, the sustained long-term decline is attributed primarily to the national zigzag kiln conversion programme and the National Clean Air Policy (NCAP 2023). SO2 declined by nearly 60%, while CO increased in rural peripheries by up to 103%, signalling a growing rural energy poverty crisis. Islamabad recorded the highest mean NO_2 concentration (8.48×10^{-5} mol/m²), surpassing Lahore for the first time. Mann-Kendall trend analysis identified 38.7% of divisions with statistically significant PM2.5 decreases and no division with a significant increase. The Lahore, Faisalabad and Gujranwala corridor was identified as the highest Health Risk Index zone. These findings provide an evidence base for adaptive, division specific air quality governance in Pakistan.

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Keywords: Air Quality, Pakistan, Particulate Matter, PM2.5, Spatiotemporal Analysis

1. Introduction

Air pollution is one of the most critical environmental health threats worldwide, and the crisis is especially severe in the Global South. Central and South Asia have the worst air quality globally, with three of the most polluted countries: Bangladesh, India, and Pakistan (Iqbal & Muzamil, 2024). In this region, over 30% of cities have PM2.5 levels more than ten times higher than the WHO guideline. As a result, over 44% of the population breathes polluted air (Bin Babar, 2024). According to the World Air Quality Report 2023, Pakistan is ranked as the second most polluted country in the world with an annual average PM2.5 concentration of 73.7, which is almost 15 times higher than the guideline of the World Health Organization (Bin Babar, 2024). This pollution trend has been ongoing for years and the monitoring data since 2010 indicates significant increases in annual mean PM2.5 levels, and aerosol optical depth has risen sharply in Pakistan since 2008 (Ali et al., 2020). Exposure to PM2.5 is linked to an estimated 114,000 premature deaths each year in Pakistan reducing life expectancy by approximately 3.8 years (Bin Babar, 2024). From 2004 to 2021, particulate matter levels increased by 0.68 per year and from 1998 to 2016, the mean PM2.5 concentration rose from 37.1 to 49.6, reflecting a growth rate of 40.6% (Dilawar et al., 2023; Mariam et al., 2021). The economic impact is highly impacted and the health issues related to particulate matter is estimated to cost 1% of the nation's GDP annually (Javed et al., 2015). Lahore is known as the most polluted city globally during winter smog events with PM2.5 levels reaching hazardous levels of 192.7, resulting in increased need for medical care for respiratory and cardiovascular diseases, as revealed in a study by (Iram et al., 2025). Infants and the elderly particularly the most vulnerable to air quality degradation. Infants absorb about 1.5 to 2.5 times more pollutants than adults, leading to chances of neurodevelopmental deficits, while the elderly face increased risks of cognitive decline and neurodegenerative diseases (Narjis Naqvi et al., 2025).

The seasonal decline in air quality in Punjab commonly referred to as smog, is observed after the monsoon and winter months, typically from October to February (Tahir et al., 2025). This time of the year is recognized as a significant environmental and public health challenge (Narjis Naqvi et al., 2025). The highest average levels of PM2.5 over the Indo-Gangetic Plain (IGP) which includes Punjab occur after the monsoon period from October to December (166) and winter season from January to February (145) as

per study by (Mogno et al., 2021). Smog poses a serious issue in Lahore during the winter season. A survey indicated that 91% of respondents felt the negative impacts of smog, with 41% specifically affected during the winter months (Iram et al., 2025). This crisis is further increased due to the transboundary pollution. HYSPLIT trajectory modeling reveals that emissions from agricultural residue burning in Indian Punjab significantly affect NO2 levels across the border during the smog season (Zeeshan, 2025). Karachi and Lahore rank among the highest for air pollution and related health issues, largely due to industrial activity and traffic emissions. In 2023, Islamabad recorded its highest annual PM2.5 concentration (42.4), surpassing WHO guidelines by nearly eight times and PM2.5 concentrations in Lahore were recorded at 99.5, nearly twenty times higher than WHO's recommended limit (Bin Babar, 2024). According to study conducted from 2020 to 2022, pollutants from industrial sources in Karachi exceeded permissible levels, the PM2.5 level reached over 180 while some areas in Lahore, such as Jalo, have reported PM2.5 levels up to 62 times higher than WHO recommendations (Iram et al., 2025).

The current policy remains inefficient due to a data drought and weak implementation plan. The absence of data complicates our understanding of source contributions. For example, the transport sector produces about 62% of urban NO2 and 33% of particulate matter (Narjis Naqvi et al., 2025). Pakistan is still stuck at Euro II emission standards and are behind the Euro VI benchmarks of the neighboring countries. It is because there is no compelling evidence to push for stricter regulations (Bin Babar, 2024). When we compare research output, Pakistan reveals a sharp contrast to China, which produced 239 source apportionment studies from 1987 to 2017. In more recent years, Pakistan can only claim few verified published studies. This weakness in source apportionment data lowers our ability to pinpoint crucial contributors behind smog events. Policymakers are left to tackle with incomplete information, uncertain whether to hold down on brick kilns or lay restriction on vehicle traffic (Bin Babar, 2024). Ground stations cover a mere 1.25% of the spatial region in Lahore division. Frequent disruptions in their operation impede any chance of continuous temporal analysis (Ahmad et al., 2025). While past studies highlight rising particulate concentrations in Pakistan, they often overlook the changing makeup of particulate pollution. Understanding this transition is vital for crafting effective mitigation strategies. Many existing studies focus on individual criteria pollutants, and few have tried to employ a multi-pollutant model and then can differentiate between emission sources, such as urban vehicle NO2 emission, industrial coal combustion releasing SO2 or agricultural biomass burning CO. Lastly, the link between urbanization and environmental degradation is acknowledged, yet comprehensive studies remain scarce. We need to statistically quantify relationships between specific Land Use Land Cover (LULC) classes like urban, cropland, and forest percentages and pollution trends nationwide, employing correlation and regression techniques (Dilawar et al., 2023).

Despite this accumulating evidence, significant knowledge gaps persist at the national scale. First, existing studies are predominantly single-city (Hamid et al., 2019; Khan et al., 2023; Zeeshan, 2025) or limited to a small number of urban centres (Ali et al., 2020: four cities; Khan et al., 2021: three macro-regions), precluding national-scale inference. Second, no study has simultaneously characterised long-term spatiotemporal trends across five key pollutants including PM2.5, PM10, NO2, SO2, and CO at the division administrative level across all provinces of Pakistan. Third is that ground based monitoring studies remain temporally less (Tabinda et al., 2020) or outdated (Hamid et al., 2019) while satellite analyses tend to focus on either a single pollutant like NO2 only (Zeeshan et al., 2025) or a narrow temporal window, 23 days (Ali et al., 2020). Critically, the confounding influence of the COVID-19 lockdown 2020 to 2021 on apparent long term pollution trends has not been statistically separated from structural, policy driven changes such as the national zigzag kiln conversion programme in any prior Pakistan study, risking misattribution of temporary reductions to sustained policy effectiveness. The present study addresses these gaps by: (i) presenting the first national, division level analysis of five pollutants using multi-sensor satellite observations spanning 2018 to 2025; (ii) applying Mann-Kendall

non-parametric trend analysis at the administrative division level; (iii) explicitly quantifying and separating COVID-19 lockdown effects from structural emission trends; and (iv) attributing pollution changes to key policy interventions and land-use dynamics across all provinces of Pakistan.

This study aims to provide the first comprehensive, division level analysis of air quality drivers and impacts in Pakistan. The objectives are as follows.

i. Apply Mann-Kendall trend analysis to check the spatiotemporal trend of significant pollution across all divisions and identify emerging locations beyond the known cities.
ii. Link pollution concentrations to specific landuse drivers and demographics using correlation analysis.
iii. Develop a health risk index and decoupling analysis to map population exposure and evaluate efficient urban growth relative to emissions.

2. Materials and Methods

2.1 Study Area

The study location in Figure 1 shows the Islamic Republic of Pakistan, located in South Asia between latitudes 23° and 37° N and longitudes 60° and 78° E. Pakistan shares international borders with India, China, Afghanistan, and Iran to the East, North, and West, while the Arabian Sea forms its southern coastline, lying on the western side of the Indo-Gangetic Plain (IGP). This alluvial plain is aligned with the Himalayan, Karakoram, and Hindukush mountain ranges to the north, creating a topographic bowl that traps emissions in the region. The climate in Pakistan is mostly arid to semiarid and has four seasons including cool dry winter (December to February), a hot dry spring (March to May), a monsoon summer (June to September), and monsoon retreating season (October to November). Over the past few decades, a different fifth season has been created, which is known as the smog season and usually covers the period between October and January. Certain weather conditions during this period, including thermal inversion, low winds, and high relative humidity, which contributes to the deterioration of the quality of the air because they contribute to the secondary development of particulate matter and consequently compound

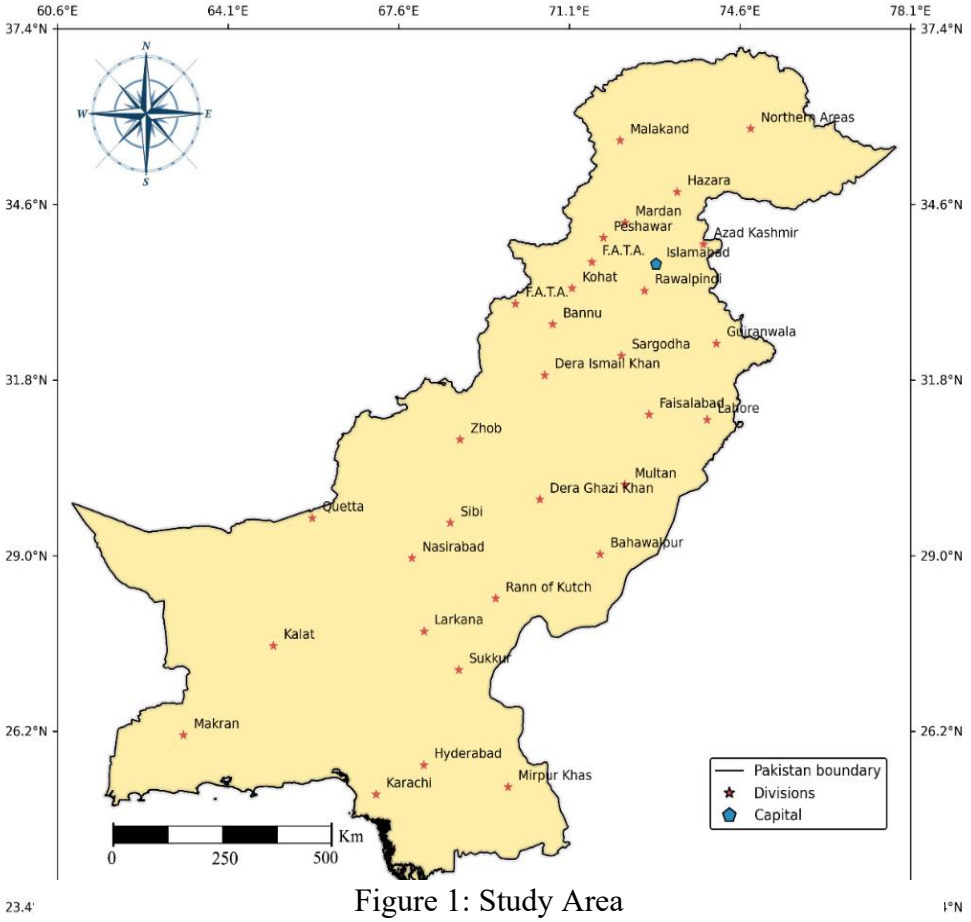


Figure 1: Study Area

the smog haze. The 2023 statistics show that the population of Pakistan is more than 241 million, which makes it the fifth most populated country in the world, one of the fastest growing urbanized states in South Asia (Pakistan Bureau of Statistics, 2023). The population distribution is highly skewed with most people concentrating around the fertile Indus river basin the Punjab and Sindh provinces, but the western provinces, particularly the Balochistan province, are lowly populated. Such population pressure creates high competition in the use of land. The research region is characterized by a complex mosaic of agricultural land, which supports the agrarian economy (a good portion, about 40%, of the total area), and urban built-up areas developing very fast like Lahore, Karachi and Faisalabad. This creates mixed source pollution such that agricultural residue burning in rural areas mixes directly with automobile and industrial emissions that occur in growing megacities.

2.2 Data Acquisition

This paper uses Earth Observation (EO) data to analyze the complex factors influencing air quality. The data covers atmospheric constituents, land surface dynamics, and population distributions. Table 1 shows the details of the parameters, sources, and their units. We utilized GEE cloud computing platform to access and manage the datasets, ensuring continuity throughout the study period from 2018 to 2025. Due to the limited availability of ground monitoring stations in Pakistan, we were unable to validate the satellite-derived concentrations with ground measurements directly. Instead, we compared the derived pollutant concentrations with earlier ground-based studies conducted in major Pakistani cities such as Lahore, Islamabad, and Karachi. The satellite-derived levels were consistent with the ranges stated in these studies within ±15% of the reported values validating the available measurements.

Table 1: Description of dataset used in this study

Variable	Dataset Source	Unit	Description
PM2.5	GHAP - CAMS	$\mu g/m^3$	Micrograms per cubic meter.
PM10	MERRA-2 - CAMS	$\mu g/m^3$	Micrograms per cubic meter.
NO2	Sentinel-5P	mol/m^2	Moles per square meter.
SO2	Sentinel-5P	mol/m^2	Moles per square meter.
CO	Sentinel-5P	mol/m^2	Moles per square meter.
Population	GHSL- POP	Count	Total number of people.
pct_{urban}	MODIS LULC	%	Percentage (0–100) of district area.
pct_{crop}	MODIS LULC	%	Percentage (0–100) of district area.
pct_{forest}	MODIS LULC	%	Percentage (0–100) of district area.

2.2.1 Atmospheric Pollutants

Trace gases such as nitrogen dioxide (NO2), sulfur dioxide (SO2), and carbon monoxide (CO) were obtained from the Sentinel-5 Precursor (Sentinel-5P) satellite, launched by the European Space Agency (ESA) in October 2017. The data utilized the Level 3 offline product from the TROPOMI spectrometer, which has a high spatial resolution of 5.5 x 3.5 km, which was improved from 7 x 3.5 km in 2019. TROPOMI was chosen for its superior signal-to-noise ratio compared to earlier missions, allowing for accurate detection of polluted urban areas. Column-density measurements (mol/m^2) were aggregated into annual data, applying a cloud cover threshold of less than 30% to filter out low-quality pixels.

For fine particulate matter (PM2.5) data from 2018 to 2025, we used the GHAP (Global High Air Pollutants) dataset, a machine learning-based model that integrates satellite aerosol optical depth with

ground monitoring data at a high resolution of 1 km. For validation, we combined this with the CAMS (Copernicus Atmosphere Monitoring Service) global reanalysis product.

For NO2, SO2, and CO, only pixels with a *qavalue* greater than 0.5 were included. Specifically, for NO2, we used the *tropospheric_NO2_column_number_density product*, which presents a stratospheric subtraction algorithm to isolate ground-level emissions. Cloud screening was strictly limited to less than 30% to reduce retrieval errors caused by albedo interference.

The annual PM10 was calculated using the NASA MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) dataset. Since MERRA-2 does not provide a direct PM10 band, we derived the mass concentration from its five aerosol components: Dust Surface Mass, Sea Salt, Black Carbon, Organic Carbon, and Sulfate Surface Mass, as outlined in Equation 1.

A scaling factor of 10^9 was applied to convert the output to $\mu g/m^3$. We utilized the surface mass diagnostic bands (SMASS) rather than total column integrated mass (LOAD) to ensure the findings reflect ground level exposure.

$$PM_{10} = (M_{Dust} + M_{Salt} + M_{BC} + M_{OC} + M_{SO4}) \times 10^9 \quad (1)$$

Where M_i represents the surface mass concentration in kg/m^3 provided by the MERRA-2 M2T1NXAER product for dust, sea salt, black carbon, organic carbon, and sulfate.

2.2.2 Land Use Land Cover (LULC)

To assess the impact of landuse changes on air quality, annual land cover maps were obtained from the MODIS MCD12Q1 (Version 6) dataset at 500-meter resolution (Friedl & Sulla-Menashe, 2019). The International Geosphere Biosphere Programme (IGBP) classification was used to extract three specific class percentages for each division:

1. Urban and Built-up (Class 13): To represent the vehicular and industrial activity
2. Croplands (Class 12): To represent the agricultural residue burning pollution
3. Forests (Classes 1–5): To assess the mitigation potential of green infrastructure

2.2.3 Demographics

Population exposure was calculated using the Global Human Settlement Layer (GHSL-POP) launched by the (European Commission Joint Research Centre, 2019). This dataset provides high-resolution (100 m) population distribution grids. Population data was also validated with data from (Pakistan Bureau of Statistics, 2017) and (Pakistan Bureau of Statistics, 2023).

2.3 Statistical Analysis and Modeling

To show spatiotemporal dynamics and identify the drivers of air quality degradation a robust statistical framework was implemented using the Python data science ecosystem like Pandas, scikit-learn, PyMannKendall. (Hussain & Mahmud, 2019). The analysis is divided into four distinct phases which are trend detection, driver identification, typology classification, and impact assessment.

2.3.1 Spatiotemporal Trend Analysis

We used non-parametric statistical tests to assess the long-term pollution trajectories from 2018 to 2025 for each division.

1. Mann Kendall (MK) Test was applied to determine the presence of monotonic trends in pollutant concentrations. A trend was considered statistically significant if the p-value was less than 0.05 ($p < 0.05$) at a 95% confidence interval (Mann, 1945) (Kendall, 1975).
2. Sens Slope was calculated to quantify the magnitude which is the rate of change per year. This allowed for the identification of emerging divisions displaying the sudden rates of degradation (Sen, 1968).

While the study period provides a relatively short time series for traditional trend detection, the use of the non-parametric Mann-Kendall test is appropriate as it does not assume a normal distribution and is not open to the outliers typically found in seasonal air quality data.

To explicitly account for the COVID-19 lockdown period, the study period was divided into three sub-periods: pre-lockdown (2018–2019), lockdown-affected (2020–2021), and post-lockdown (2022–2025). Mean pollutant concentrations were computed separately for each sub-period, and an interrupted time-series framework was applied to quantify the magnitude of the lockdown-induced disruption relative to the underlying structural trend. This approach allows separation of the transient lockdown effect from long-term, policy-driven emission changes such as the zigzag kiln conversion programme, ensuring that reported trend magnitudes are not confounded by the anomalous 2020 lockdown period.

2.3.2 Driver Identification

To understand the impact of anthropogenic and natural factors, we created correlation matrices to assess the linear relationships (r) between annual mean concentrations of particulate matter (PM2.5, PM10, NO2, SO2, CO) and land use variables (*pcturban, pctcrop, pctforest*). A positive correlation between a pollutant and percent urban typically indicates an urban industrial or vehicular source. Similarly, a positive correlation with percent crop suggests the burning of agricultural residue, while a negative correlation with percent forest often indicates the mitigating effects of green infrastructure.

2.3.3 Typology Classification (K-Means Clustering)

The study utilizes the k-means clustering method (MacQueen, 1967), an unsupervised machine learning algorithm, to classify the divisions of Pakistan into various pollution typologies. This algorithm grouped divisions based on similarities in population density, urbanization rates, and levels of multiple pollutants. K=4 clusters to identify megacity hotspots, industrial zones, agricultural regions, and rural baselines. To ensure that population figures did not skew the distance measurement prior to clustering, Min-Max scaling is applied to the data features (Pedregosa et al., 2011), as per Equation 2.

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (2)$$

2.3.4 Impact Assessment Metrics

To determine the human and policy aspect of the crisis, two derived measurements were computed.

1. The Health Risk Index (HRI), which is the product of pollutant concentration and total population (Ci x Pi). This spatially weighted measure identifies divisions with high exposure and significant population density, highlighting priority areas for public health intervention.
2. The Decoupling index assesses the effectiveness of urban development by comparing pollution and population rates against a 2018 baseline (Index2018 = 100). Deviations from this baseline indicate either green growth (pollution < population) or inefficient urbanization (pollution > population).

3. Results

3.1 Spatiotemporal Trends of Air Quality

3.1.1 National and Provincial Trends

Timeseries analysis reveals a complex air quality curve in Pakistan, challenging the common narrative of uncontrolled environmental destruction. Notably, fine particulate matter (PM2.5) concentrations show a significant change between 2019 and 2020, as illustrated in Figure 2. Starting from a baseline of 60.85 µg/m³ in 2018, the national average of PM2.5 dropped sharply to 35.20 µg/m³ by 2025, marking a

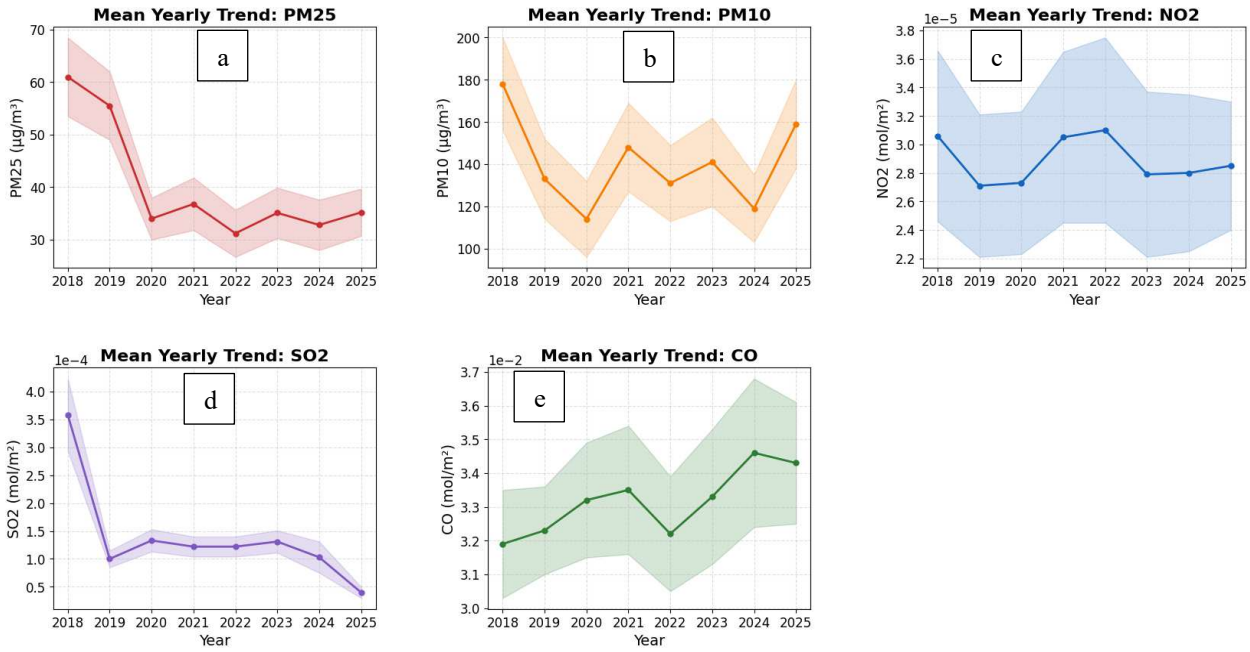


Figure 2: Mean yearly trends of air pollutants (a) PM2.5 (b) PM10 (c) NO2 (d) SO2 (e) CO

substantial 42.1% reduction. A notable shift occurred in 2020, with a concentration of 34.05 µg/m³, coinciding with the COVID-19 pandemic, after which levels stabilized rather than returning to pre-2019 figures. Coarse particulate matter, PM10 displayed high annual instability, dropping in 2020 but rising to 158.71 $\mu g/m^3$ by 2025, indicating an increase in regional dust sources. Tropospheric NO2 concentrations remained resilient, experiencing a slight dip in 2019 to 2.71 x 10^{-5} mol/m² but recovering to 2.92 x 10^{-5} mol/m² by 2025, reflecting a net 7.7% increase and persistent vehicular and urban emissions. SO2 levels decreased by 59.9% from 2019 baselines, dropping to 4.00 x 10^{-5} mol/m² in 2025. CO followed a similar trajectory to NO2, increasing by 5.9% since 2019, indicating rising combustion emissions. This trend is consistent across provinces, as illustrated in Figure 3, where all provinces showed a decrease in PM2.5 concentrations by 2025, and NO2 levels exhibited a similar pattern, except for Islamabad, which had higher NO2 concentrations but also a decreasing trend.

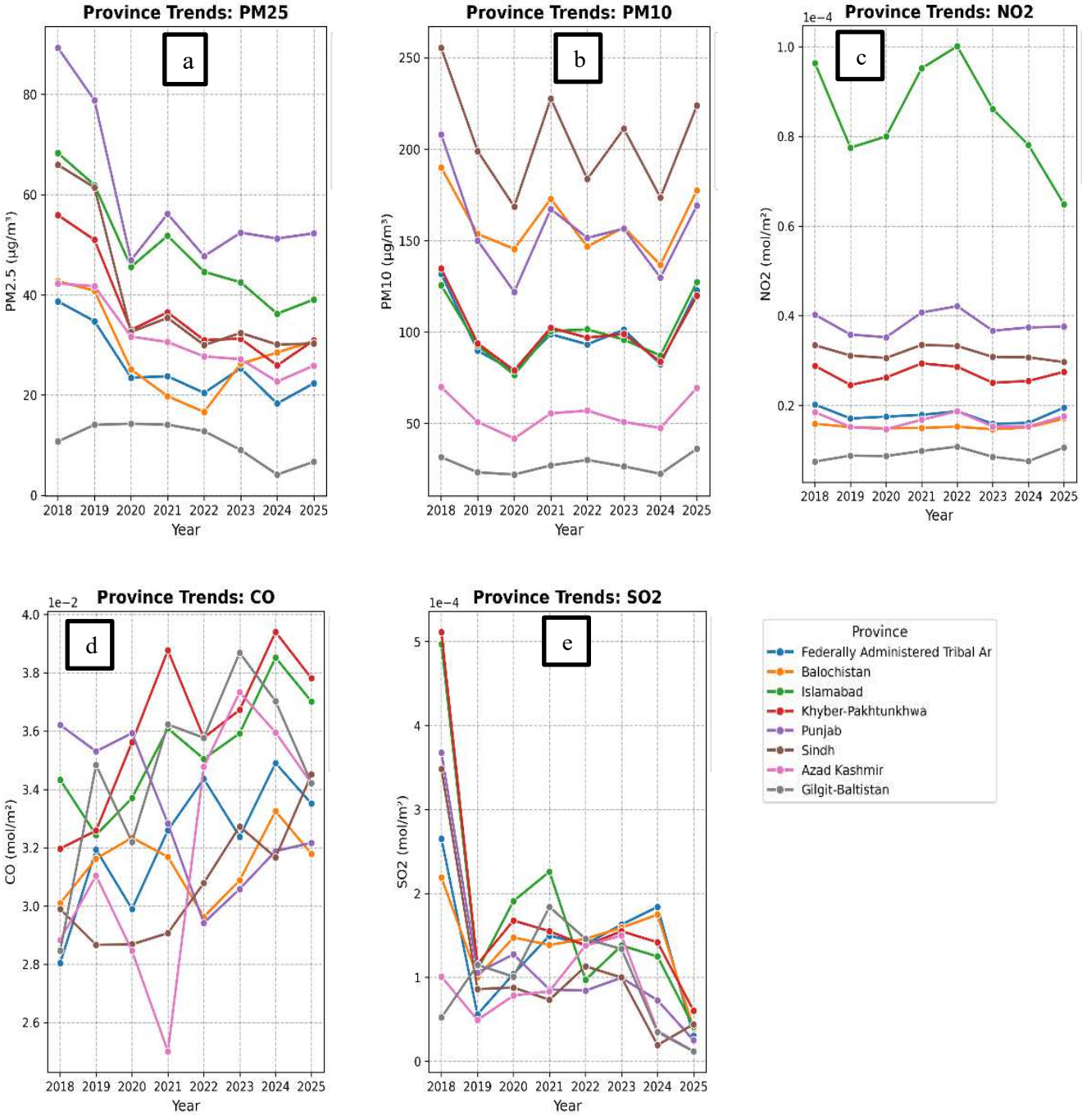


Figure 3: Province level mean yearly trend of all pollutants including: (a) Particulate Matter 2.5 (b) Particulate Matter 10 (c) Nitrogen Dioxide (d) Carbon Monoxide (e) Sulfur Dioxide

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281 *3.1.2 Decoupling Analysis*

The trends can be normalized if compared to the national population growth index (Base 2018 = 100), allowing us to evaluate the efficiency of urban development in Pakistan, as illustrated in Figure 4. The study region experienced a stable demographic growth of +15.5% from 2018 to 2025. Notably, PM2.5, PM10, and SO2 levels have decreased without a corresponding increase in population. While these pollutants continue to rise, although at slower rates with CO projected to reach 107.5 by 2025, their growth rates of +7.7% and +5.5% are lower than the population growth rate of +15.5%. This shows that the efficiency increase in the transport and combustion sectors have been very low.

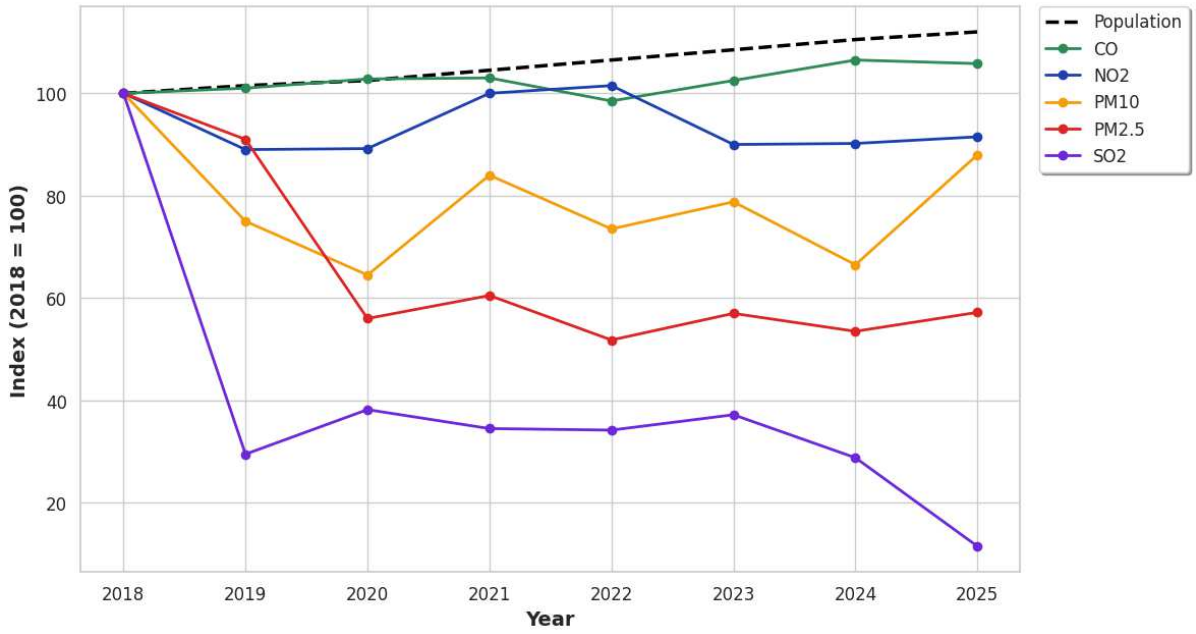


Figure 3: Decoupling analysis of pollutants vs population with 2018 as the baseline for trend normalization

3.2 Spatial Distribution and Hotspots

3.2.1 Division Rankings

Spatial analysis highlights the division rankings for various pollutant types, as outlined in Table 2.

Islamabad (8.48 x 10^{-5} mol/m^2) has the highest mean NO2 concentration at with, surpassing Karachi (5.78 x 10^{-5} mol/m^2) and Lahore (5.72 x 10^{-5} mol/m^2). This makes the federal capital as a notable area for vehicle density.

Lahore is recognized as the fine particulate smog center with a concentration of 73.01, while Kohat leads in sulfur emissions with a concentration of 1.75 x 10^{-4} mol/m². Additionally, sulfur emissions are increasing in the Khyber Pakhtunkhwa region, with Hazara, Malakand, and Dera Ismail Khan among the top five contributors of SO2, as detailed in Table 2.

In contrast, the geography of coarse pollution differs from urban centers. Bahawalpur ranks highest for PM10 at 238.56 and CO at 0.0366 mol/m², followed by Multan at 180.82, highlighting the effects of topography and the arid desert environment on biomass burning practices in southern Punjab.

Table 2 : Division ranking of top 5 hotspot divisions in Pakistan for all pollutants

Rank	**PM2.5 ($\mu g/m^3$)**	**NO2 (x10^{-5} mol/m^2)**	**PM10 ($\mu g/m^3$)**	**SO2 (x10^{-4} mol/m^2)**
1	Lahore (73.0)	Islamabad (8.48)	Sukkur (264.07)	Kohat (2.22)
2	Gujranwala (68.6)	Karachi (5.78)	Bahawalpur (238.56)	Sukkur (2.00)
3	Faisalabad (67.7)	Lahore (5.72)	Makran (227.511)	Hazara (1.94)

4	Multan (65.3)	Peshawar (4.44)	Rann of Kutch (207.30)	Malakand (1.93)
5	Bahawalpur (51.3)	Gujranwala (4.15)	Mirpur Khas (202.92)	Dera Ismail Khan (1.90)

3.2.2 Spatiotemporal Rate of Change

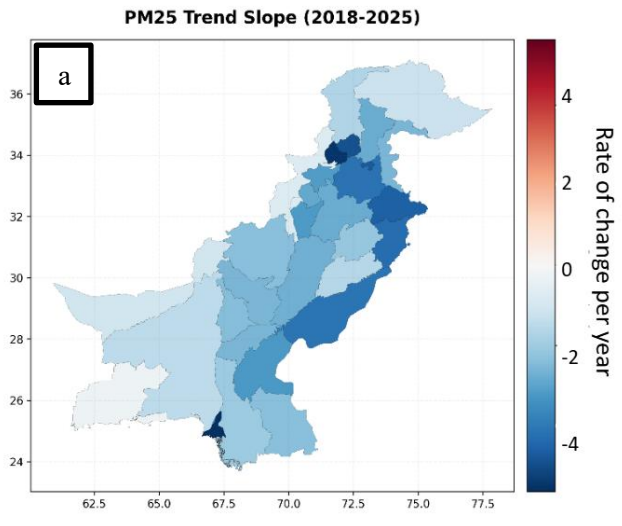
Annual mean concentrations show the pollution levels. The Mann-Kendall test and Sens Slope estimator reveal the statistical significance and magnitude of these trends at the division level. The results of the MK analysis for 31 key divisions are shown in Table 3, and the Sens Slope estimator is plotted in Figure 5.

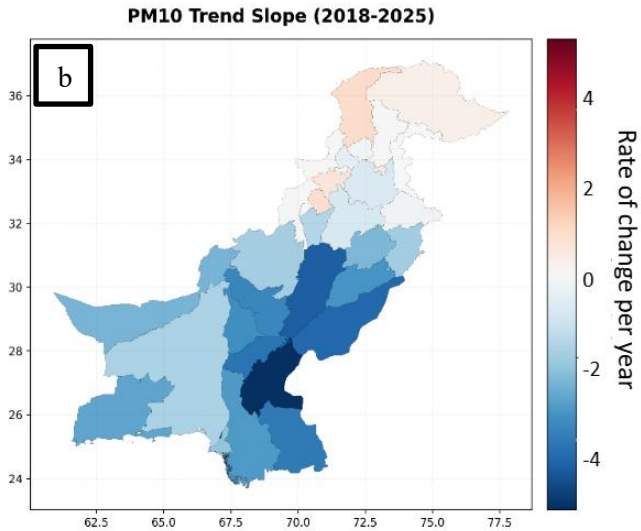
Table 3 : Summary of MK Test trend for all pollutants in all divisions of study area

Pollutant	Divisions	Increasing	%Increasing	Decreasing	%Decreasing	No Trend	%No Trend
CO	31	5	16.1	0	0	26	83.9
NO2	31	1	3.2	1	3.2	29	93.5
PM10	31	0	0	0	0	31	100
PM2.5	31	0	0	12	38.7	19	61.3
SO2	31	0	0	9	29	22	71

The division analysis indicates a statistically significant decreasing trend in PM2.5 for 38.7% of divisions, with no divisions showing a significant increase. The most notable improvements were observed in large urban divisions. Karachi (-5.64 $\mu g/m^3$ per year), Peshawar (-5.50 $\mu g/m^3$/year) and Mardan (-4.91 $\mu g/m^3$/year) had the highest rate of reduction.

PM10 shows no consistent trend across the divisions except for Sukkur showing high decrease with a slope of -6.206 $\mu g/m^3$/year then followed by Rann of Kutch with a slope of -5.401 $\mu g/m^3$/year and then Dera Ghazi Khan with -5.108 $\mu g/m^3$/year.





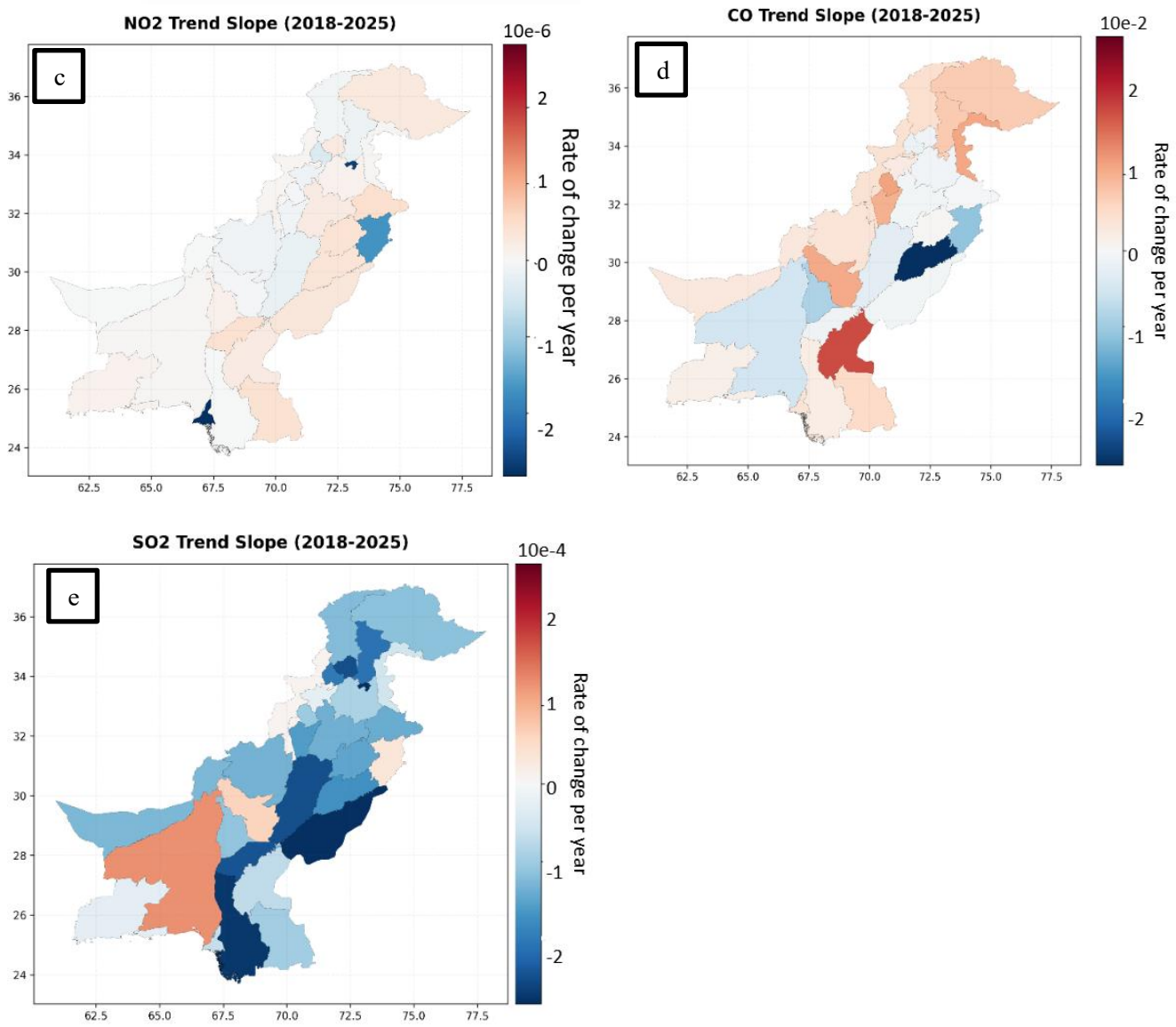


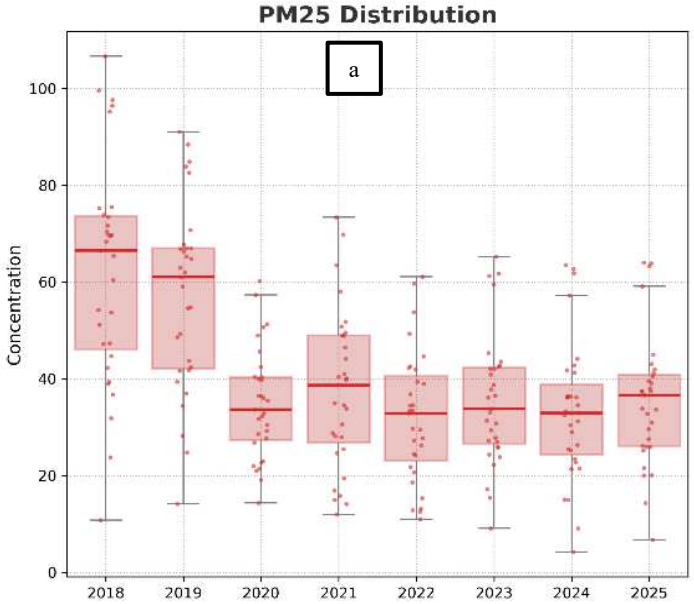
Figure 5 : Sens Slope estimation for pollutants: (a) PM2.5 (b) PM10 (c) NO_2 (d) CO (e) SO_2

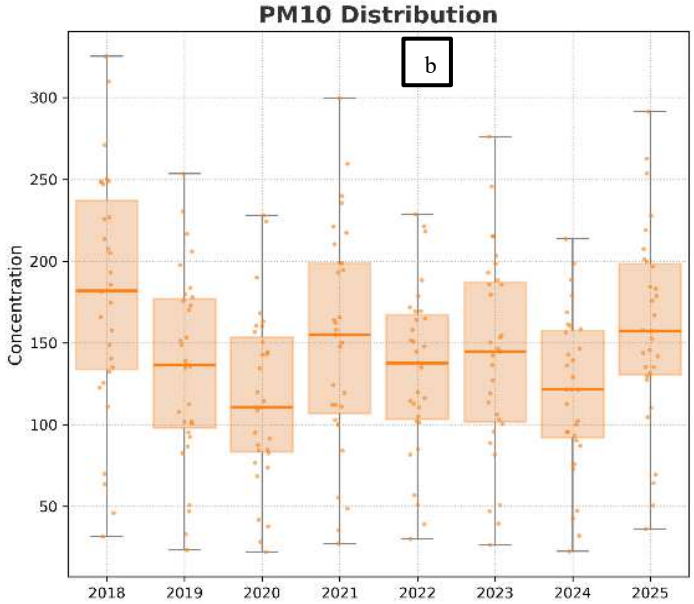
CO is the only pollutant showing a notable positive trend with 16.1% of the divisions showing a strong increasing trend, with none of the divisions reported improvement. This rise was primarily observed in the peripheral areas of Punjab rather than its industrial center. Sibi (Balochistan) recorded the highest increase (+1.15 x 10^{-3} mol/m^2 per year), followed by Dera Ismail Khan (+1.07 x 10^{-3}) and Hazara (+7.93 x 10^{-4}). In contrast, SO2 displayed a declining trend, with 29% of the divisions experiencing decreases of about 9 out of the 31 divisions. The most significant reductions were recorded in Bahawalpur (-3.20 x 10^{-5} mol/m^2/year) and Hyderabad (Q = -3.10 x 10^{-5}). Similar to the trend for PM2.5, the increase in SO2 concentrations was not statistically significant across any divisions. NO2 remained relatively stable, with 93.5% of divisions showing no major trends. Only Mirpur Khas experienced a significant increase (+4.00 x 10-7 mol/m2 per year), while Karachi showed a significant marginal change. The mean and standard deviation of the parameters can be observed in Table 4.

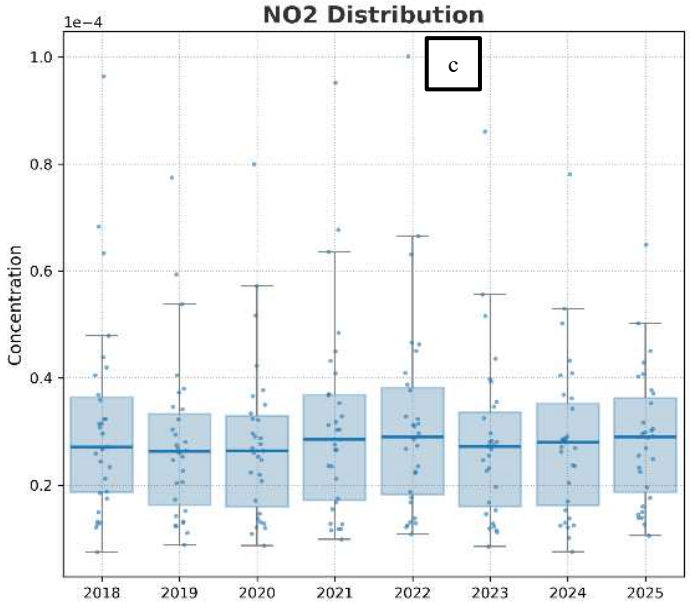
Table 4 : Statistical summary of all pollutants for all divisions in Pakistan from 2018 to 2025.

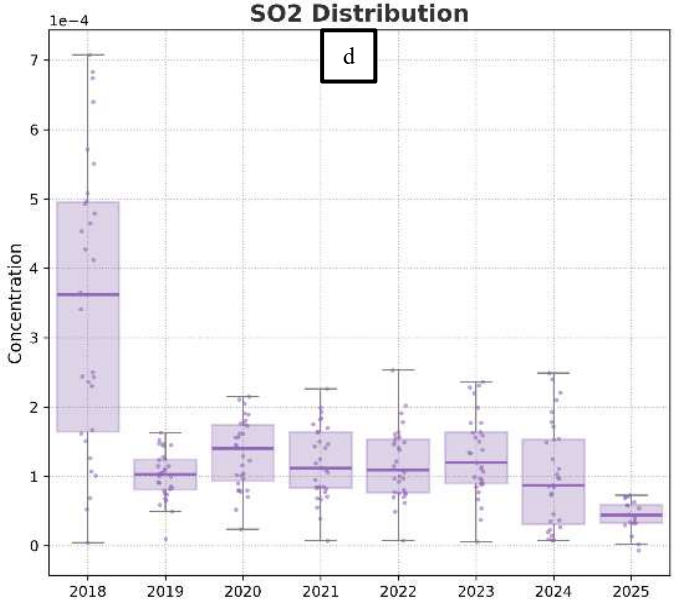
	PM2.5 ($\mu g/m^3$)	**NO2 (mol/m²)**	**PM10 ($\mu g/m^3$)**	**SO2(mol/m²)**	**CO (mol/m²)**
Mean	40.37	2.88 x 10^{-5}	140.32	1.39 x 10^{-4}	3.31 x 10^{-2}
Standard Deviation	18.94	1.58 x 10^{-5}	60.72	1.26 x 10^{-4}	5.28 x 10^{-3}

3.2.3 Distribution & Inequality









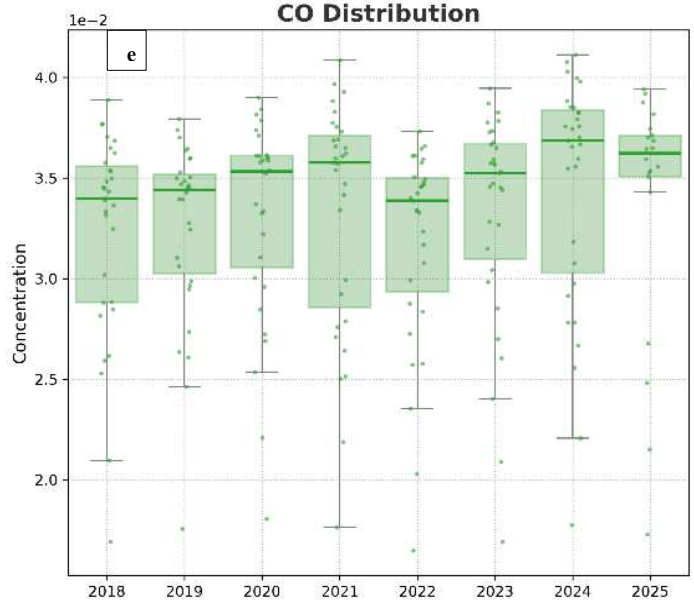


Figure 4: Boxplot of distribution of different pollutants including : (a) Particulate Matter 2.5 (b) Particulate Matter 10 (c) Nitrogen Dioxide (d) Sulfur Dioxide (e) Carbon Monoxide

The boxplot analysis (Figure 6) highlights a spatial gap in pollution exposure. PM10 shows extremely high standard deviation (60.7), with values ranging from a minimum of 22.1 to a maximum of 325.2. NO2 maximum value is (1×10^{-4}) nearly 4 times higher than the mean (2.9×10^{-5}). Most divisions have low NO2, but a few (like Islamabad and Lahore) are three to four times worse than the national average.

3.3 Population Exposure and Health Risk Assessment

The division rankings show areas with the highest concentrations of pollutants, while the Health Risk Index incorporates demographic data to pinpoint divisions with the greatest human exposure to these pollutants (HRI = Ci × Pi). Figure 7 lists the top ten divisions with the highest collective exposure risk. Lahore ranks first in both concentrations and health risks for PM2.5 and NO2. The combination of poor air quality and high population density makes Lahore a top priority for national health interventions. In contrast, divisions like Bahawalpur, which ranks highest for raw PM10 dust concentrations, fall lower in risk rankings due to their lower population density. Karachi and Faisalabad, even with lower concentration, are ranked higher in the HRI, with Karachi having the highest PM10 concentration. Their large populations increase the impact of average pollution levels, converting them into severe public health concerns.

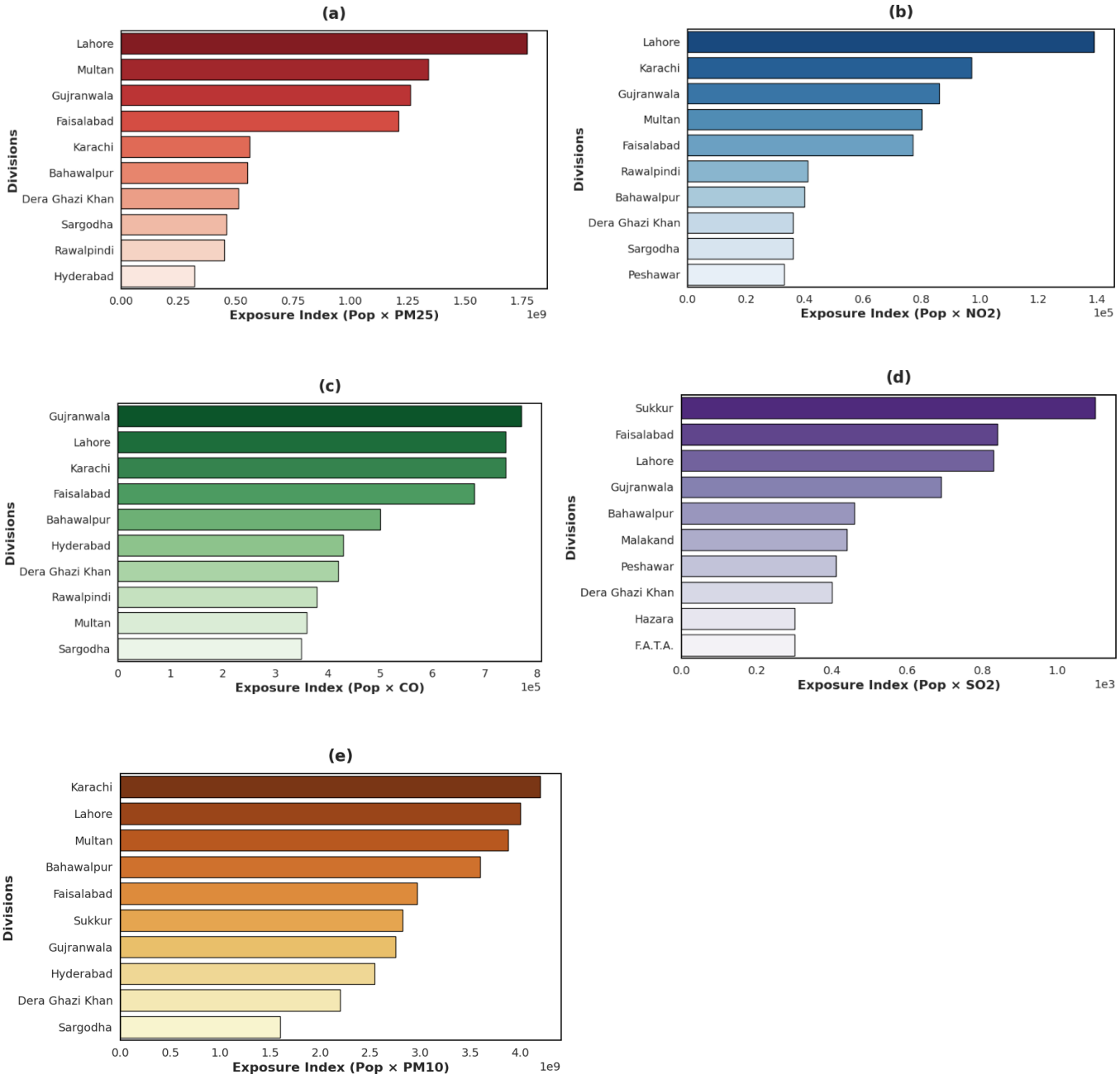


Figure 7 : Top 10 Health Risk Index in 2025 for (a) PM2.5 (b) NO_2 (c) CO (d) SO_2 (e) PM10

The HRI exposes cities like Gujranwala and Sialkot as high priority areas. Although their pollution rates are not as high as the most exposed ones, their high population density and its rapid growth led to the overall respiratory load that is almost equal to the one of provincial capitals.

3.4 Drivers of Pollution (Source Apportionment)

3.4.1 Land Use Correlation

The correlation between landuse variables and the concentration of pollutants is measured using Pearson correlation analysis and can be seen in Figure 8.

Urbanization (*pct_urban*) has the highest positive correlation with NO2 ($r = 0.78$) and a minimal correlation with CO ($r = 0.10$), which further strengthens urbanization as the main factor in the accumulation of NO2 and fine particulate matter.

Agriculture (*pct_crop*) has a moderate positive relationship with NO2 (r = 0.45) and strong relationship with PM2.5 (r = 0.69), pointing out agricultural tools and the combustion of crop byproducts as main causes of these contaminants.

PM10 (r = -0.49) and NO2 (r = -0.15) demonstrate negative correlations with vegetation, suggesting a moderating effect specifically indicating that increased forest cover is associated with lower levels of ambient pollutants.



Figure 8 : Correlation matrix for pollutants vs LULC parameters from 2018 to 2025

3.5 Pollution Characterization and Typologies

3.5.1 Pollution Ratios

The analysis of air pollution in Pakistan directed on the dynamic physical properties using the fine fraction ratio (PM2.5/PM10). This ratio helps identify the sources of particulate matter, where a ratio above 0.4 indicates combustion sources and a ratio below 0.25 to resuspended dust or soil. Table 5 provides an overview of the development of this fine fraction ratio.

Table 5 : Pollution characterization ratios PM2.5/PM10

Year	PM2.5 ($\mu g/m^3$)	PM10 ($\mu g/m^3$)	Ratio (PM2.5 / PM10)	Regime Classification
2018	60.85	177.72	0.34	Mixed (Dust + Smoke)
2019	55.62	132.55	0.42	Smoke-Dominant
2020	34.05	113.83	0.30	Mixed
2021	36.87	148.35	0.25	Dust-Dominant
2022	31.37	130.68	0.24	Dust-Dominant
2023	35.18	141.56	0.25	Dust-Dominant
2024	32.84	119.07	0.28	Mixed
2025	35.20	158.71	0.22	Highly Dust-Dominant

In 2019, the national mean ratio was 0.42, indicating a higher proportion of fine particulate matter, making it a smoke-dominant year. By 2025, the national mean ratio decreased to 0.22. This shows that while PM2.5 mass concentrations have declined, the proportion of coarse dust PM10 has increased in total mass.

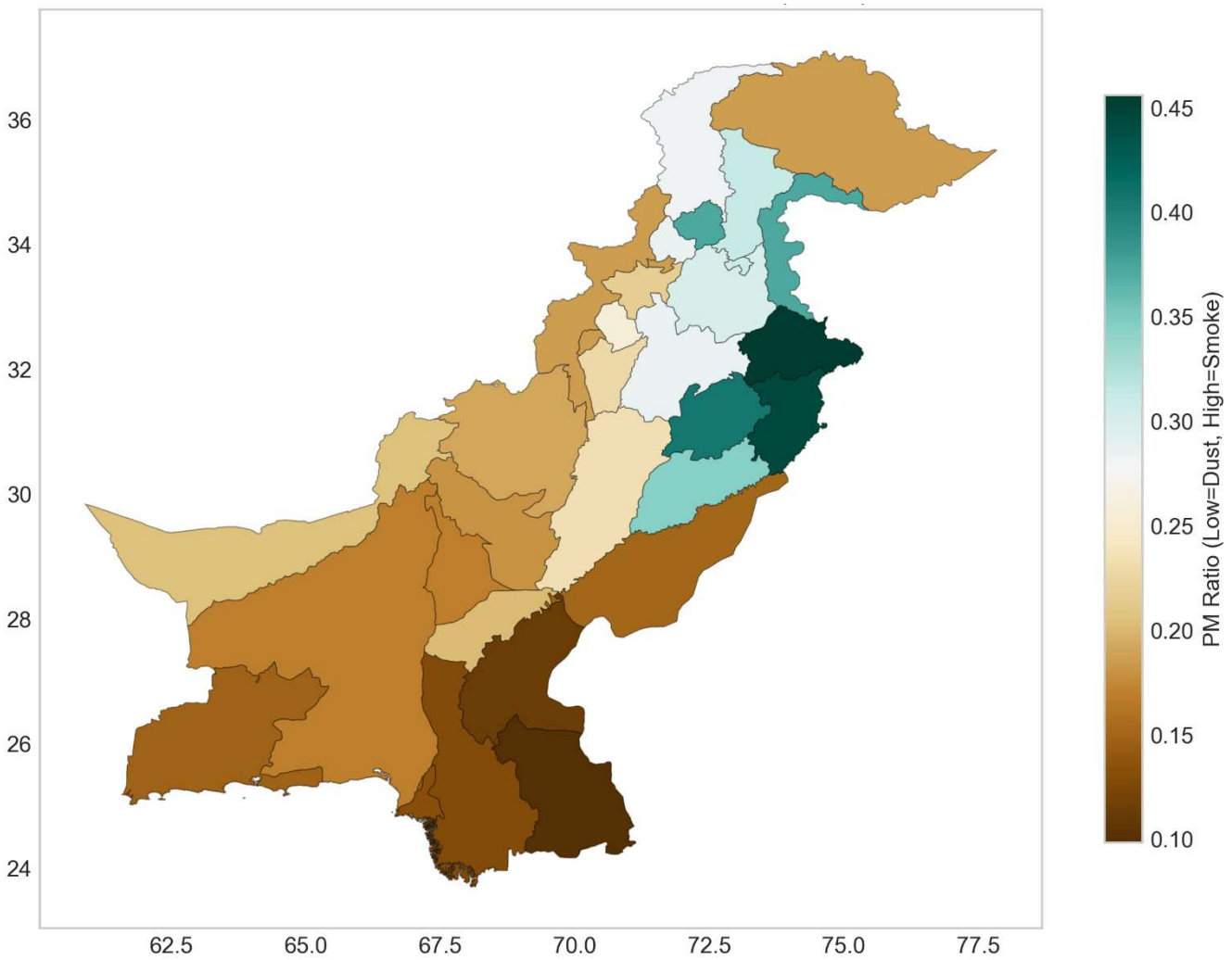


Figure 9: Pollution Characterization Ratio PM2.5/PM10 for all divisions in Pakistan in 2025.

3.5.2 Division Typologies (Cluster Analysis)

The classification of divisions based on pollution and land use characteristics, determined through cluster analysis (k = 4), is detailed in Table 6.

Cluster 0 has the highest average SO2 level (1.48 x 10^{-4} mol/m^2) and low urbanization (0.34%). Cluster 1 has the highest mean population (16.7 million) and the highest mean PM2.5 concentration (52.0 $\mu g/m^3$). Cluster 2 shows the highest mean PM10 concentration and low PM2.5/PM10 ratios, representing mineral dust profile. Cluster 3 has had the highest mean urbanization (17.5%) and mean NO2 (5.62 x 10^{-5} mol/ m^2).

Table 6 Cluster analysis results for k=4 clusters

Typology	Cluster	Population in millions (Avg)	Urban (%)	PM2.5	NO2 (mol/m2)	SO2 (mol/m2)	Count
Industrial Sulfur Zones	0	3.8	0.3%	29.0	2.08e-05	1.48e-04	10

Anthropogenic Smog Belt	1	16.7	2.8%	52.0	3.72e-05	6.60e-05	8
Dust Zones	2	4.4	0.6%	26.6	2.05e-05	6.25e-05	11
Urban Traffic Cores	3	10.4	17.5%	34.1	5.62e-05	7.31e-05	3

Similarly, in Figure 10, we can see the clustered classification of the divisions of Pakistan

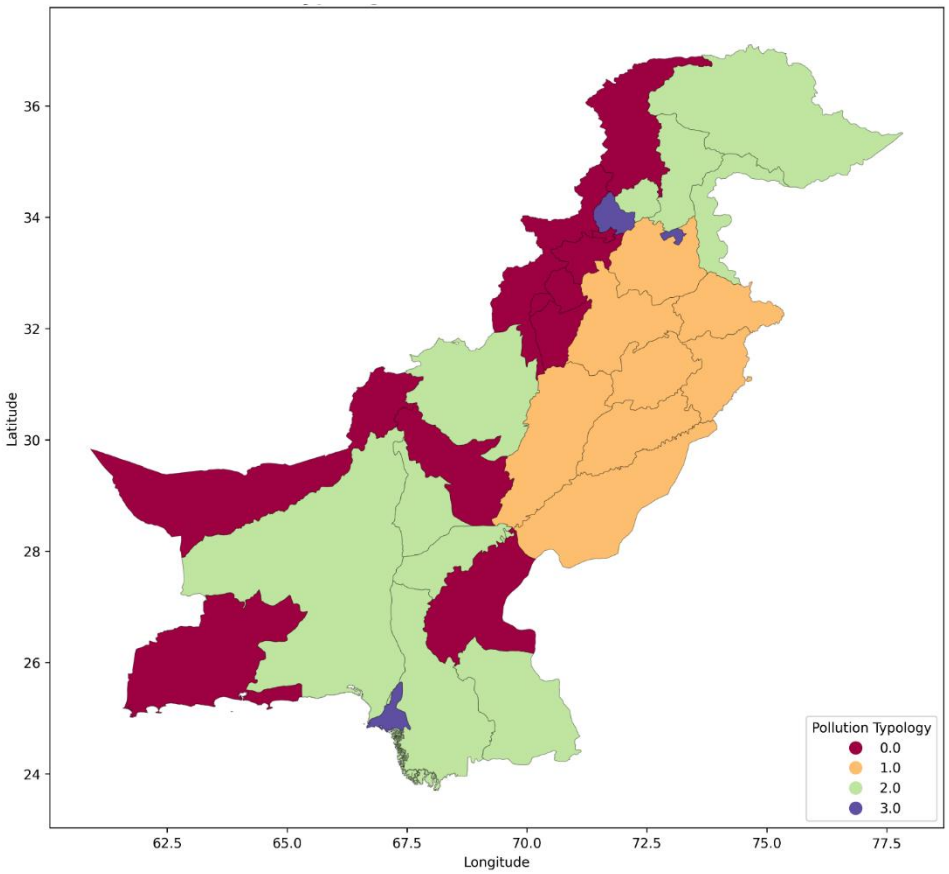


Figure 5: Pollution Typologies using K-means classification (k=4) for all divisions in Pakistan.

4. Discussion

One of the key findings of this study is the 42.1% decrease in national PM2.5 levels from 2018 to 2025, declining from 60.85 to 35.20 µg/m³. These figures are like recent data from Islamabad, where average and median concentrations were recorded at 44.09 µg/m³ and 41.69 µg/m³, respectively (Nazir & Shah, 2023). This trend differs with earlier studies which indicated a decline in Pakistan's air quality. For example, long-term records from 1998 to 2016 showed a 40.6% rise in PM2.5 levels (Mariam et al., 2021), and forecasting models created before 2021 predicted concentrations might surpass 100 µg/m³ by 2023 (Bhatti et al., 2021). Our study suggests a shift around 2019 to 2021 which aligns with the global shutdown due to the pandemic. Other studies also reported similar reductions during the lockdown phase. In Lahore, PM2.5 concentrations fell from 74.4 µg/m³ in 2019 to 44.1 µg/m³ in 2020, a 40% decline (Bin Babar, 2024). This drop matches the turning point identified in our dataset, emphasizing that the initial improvement was caused by the temporary halt in transportation and industrial operations. PM2.5 levels have not returned to previous values after the continuation of normal economic activity in 2021. This decline relates to different reforms, including the shift from traditional brick kilns to zigzag technology. Research indicates that zigzag kilns operate more efficiently, reducing particulate emissions by approximately 40% and black carbon by up to 60% compared to fixed-chimney kilns (Bin Babar, 2024). By 2021, nearly all of Punjab's 20,000 kilns had made this transition, contributing to a significant

reduction in dust and likely lowering the PM2.5 baseline of the region (Iram et al., 2025). However, several local studies from 2024 still report hazardous particulate concentrations, reaching as high as 400 μg/m³ near kiln sites, due to the ongoing use of low-quality fuels such as coal, rubber, and industrial sludge (Bin Babar, 2024). This shows that technological innovations have produced national benefits but the lack of fuel quality regulations may still have delayed the progress.

These findings challenge the existing concept that the particulate pollution is continuously worsening. Several existing studies, particularly from 2010 to 2021, were published prior to significant policy changes like the National Clean Air Policy and the widespread adoption of zigzag kilns. Our results align more closely with recent satellite-based trace-gas analyses, which suggest that emissions likely peaked around 2016 and have moderated since (Narjis Naqvi et al., 2025). Overall, the evidence indicates that Pakistan may have passed its peak particulate phase and is now experiencing a period of stabilization, even though PM2.5 concentrations remain about seven times above WHO guidelines. While there has been improvement in particulate pollution, NO2 levels continue to rise. National NO2 levels increased by 7.7% after 2019, and CO levels increased by 5.9%. According to the correlation of 0.78 between urbanization percentage and NO2 emissions highlights the direct link between urban growth and NO2 emissions. Unlike PM2.5, which can be managed by addressing point sources like kilns, NO2 is closely associated with vehicle density. While population growth has been slower than the increase in NO2 levels, the transport sector continues to expand at a rate which weakens efficiency improvements. For example, vehicle density in Lahore grew at an average rate of 12%, reaching 6.29 million vehicles in 2021, which represents an increase of 2.39 million vehicles during that period (Bin Babar, 2024). Approximately 70% of this traffic comprises motorcycles, and many older combustion engines remain in use. As a result, the gains from newer vehicles have been overshadowed by rapid fleet growth. Emission inventories indicate that transportation sources contribute to 48 to 62% of the total tropospheric NO2 levels in major cities across Pakistan (Narjis Naqvi et al., 2025), highlighting that traffic density is a primary source of urban air pollution. An important factor driving this trend is the outdated emissions standards in Pakistan. While neighboring countries like India and China have adopted Euro VI standards, Pakistan still adheres to Euro II regulations established in 2013. For heavy-duty diesel vehicles, Euro VI limits on particulates are approximately 25 times stricter than those of Euro II (Bin Babar, 2024). This explains why our cluster analysis shows extremely high NO2 intensity in densely populated metropolitan areas of Pakistan.

Islamabad recorded the highest mean NO2 concentration (8.48×10^{-5} mol/m²), surpassing Lahore for the first time. This is a shift from earlier judgments that considered air quality in Islamabad as relatively clean and within acceptable limits as recently as 2014 (Shahid et al., 2019). The higher concentration levels appear to correlate closely with vehicular emissions, supported by data showing higher concentrations during morning and evening rush hours (Nazir & Shah, 2023). Unlike Lahore, which has invested in a mass transportation system, including the Metro Bus and Orange Line, Islamabad's lower density encourages personal car use. Additionally, the topography created by the Margalla Hills aids the increase of NO2 in the city's air shed.

Tropospheric SO2 levels are projected to decrease by nearly 60% between 2019 and 2025. This trend corresponds to that observed in regions like Beijing Tianjin Hebei, where aggressive industrial fuel switching and strict emission regulations have been implemented (Yuan et al., 2024). The reduction aligns with Pakistan's National Clean Air Policy 2023, which aims to decrease reliance on high-sulfur fuels (Narjis Naqvi et al., 2025). Additionally, the industrial sector in Kasur uses a lot of biomass energy and it suggests potential pathways for lowering sulfur emissions. However, the significant 200% increase in SO2 levels in areas like Kalat highlights that progress is uneven and necessitates targeted inspections.

Another notable shift in pollution, according to the findings, is a substantial change in particulate matter. There has been a reduction in fine particulate pollution (PM2.5) alongside an increase in coarse particulate matter (PM10). The fine fraction has changed from 0.34 in 2018 to 0.22 in 2025 and it indicates a transition from a high combustion atmosphere to being more influenced by dust. Bahawalpur and Multan reported the highest PM10 concentration at 238.6 and 238.4 $\mu g/m^3$, respectively due to significant mineral dust

influx from the Thar and Cholistan deserts (Ali et al., 2020). Additional research indicates that PM10 levels remain well above global averages in cities like Rawalpindi, Islamabad, Lahore, and Gujranwala (Shahid et al., 2019; Tabinda et al., 2020). The observed 19.7% increase in PM10 since 2019 correlates with climate change studies that link CO2 levels to heightened soil dryness and erosion in the Sistan region and the IGP (ul-Haq et al., 2017). These findings imply that the coarse dust load in Pakistan is influenced not only by local sources, such as road dust, but also by long-range transport from Rajasthan and parts of the Middle East.

In contrast to cities like Lahore, which have stabilized CO levels, rural and semi-rural areas such as Sukkur and Hazara are witnessing significant increases in CO, with rises of 103% and 84.9%, respectively. This growing disparity between urban and rural areas is consistent with earlier studies indicating that mountainous regions often depend on wood stoves for winter heating due to limited access to natural gas (Shahid et al., 2019). The rising CO levels suggest that growing rural populations continue to depend on solid fuels. The sharp increase in Sukkur may also be attributed to inadequate waste management, as open burning remains common in many secondary cities. The strong correlation between urbanization and NO2, with a correlation coefficient of $r = 0.78$, reinforces that NO2 is primarily an urban pollutant concentrated in densely populated areas. In Lahore, transportation is the leading source of NOx emissions, contributing 3,390 tons compared to 2,296 tons from industry (Zeeshan, 2025). Additionally, the wind speed in urban environments is reduced, leading to pollutant accumulation between high-rise buildings, known as the street canyon effect from a study by (Wang et al., 2023). PM2.5 shows the highest correlation with agricultural burning, demonstrated by a correlation coefficient of $r = 0.69$ with cropland percentage. Post-monsoon burning, which involves the burning of residual crops, produces significant smoke and CO (Mogno et al., 2021), a trend evident in our data from regions like Bahawalpur and Gujranwala.

Finally, the moderate negative correlation between forest cover and PM10, with a coefficient of $r = -0.49$, suggests that vegetation acts as a natural dust filter. Previous research has shown that forests and green belts in urban areas can effectively trap coarse particles (Ahmad et al., 2025). However, deforestation in northern Pakistan has increased dust levels (Dilawar et al., 2023).

5. Conclusion

This study provides a detailed overview of air pollution in various divisions of Pakistan for the period 2018 to 2025, with a focus on various pollutants. It uses high resolution satellite images from Sentinel-5P, MODIS and MERRA-2, as well as population and land use data, instead of only ground data. The results suggest that Pakistan might be moving towards a new atmospheric condition with less combustion derived particulates and more mineral dust which would require a change in mitigation strategies from emission control to land management and dust reduction. In 2018, the dominance of smoke from fuel combustion is observed but in 2025 dust is the dominant pollutant. Following are the five takeaways from this study.

1. Nationwide PM2.5 levels have decreased by 42.1%, from 60.8 $\mu g/m^3$ to 35.2 $\mu g/m^3$, and a 15.5% population increase. This shows improvement in air quality even though population increased, probably due to measures like replacing brick kilns with zigzag technology and strict bans on burning agricultural waste.
2. The transport sector remains a problem, with a rise in NO2 levels of 7.7% closely linked to urban expansion. In Islamabad, pollution level was recorded at 8.48×10^{-5} mol/m^2 with the increase in vehicles and failure of Euro-II standards to keep pace with the technological advancements.
3. SO2 levels have dropped by nearly 60%, indicating reduced use of furnace oil in factories, possibly due to cleaner alternatives promoted by NCAP 2023. But in Kalat SO2 levels increased by 200%, indicating unregulated industrial activity.

4. CO levels have increased in rural areas, with Sukkur rising by over 100% and Hazara by nearly 85%. This trend points to a growing crisis in rural electricity consumption, as families increasingly alternate to burning wood, plant waste, or garbage due to a lack of cleaner options.
5. According to the HRI, the Lahore-Faisalabad-Gujranwala corridor is the most dangerous. Dust levels are higher in the south, but the densely populated central Punjab region also suffers from high levels of persistent PM2.5 and significant levels of NO2 pollution, making this zone a top health concern.

6. Recommendations

In accordance with the identified cluster types, we recommend an adapted governance approach and not a one-size-fits-all solution. For major cities like Islamabad, Lahore and Karachi , the institution of Low Emission Zones may be an effective measure to limit older pre-Euro II vehicles from entering the city during peak hours (8 to 11 am and 5 to 8 pm) and also promote electric bus initiatives. Since NO2 is mostly accumulated in urban areas, improving transportation in these areas could lead to a disproportionately large reduction in pollution at the national level.

For agricultural areas such as Gujranwala and Multan, the focus should be on improved management of residual crops rather than brick kilns. This includes financial incentives to farmers to use non-burning options and to plant trees and vegetation around these areas. Our research results show that forest cover and air pollution are negatively correlated (-0.49) which indicates the importance of trees in intercepting smoke from agricultural activities.

Arid cities such as Bahawalpur and Sukkur face a severe problem of trash fires, evidenced by abrupt CO spikes in smaller cities due to inadequate waste management. The local government should act on this issue immediately. Furthermore, stabilizing bare soil and creating green belts can reduce the PM10 dust, which is the main pollutant in southern regions at present.

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Data Availability Statement: The dataset used and analysed during the current study is available from the first author on reasonable request.

Conflicts of Interest: The authors declare that they have no conflict of interest.

Author Contributions

Conceptualization: F.A. and M.W.; Methodology: F.A., M.W., and Z.A.; Data acquisition: F.A. and Z.A.; Formal analysis: F.A. and Z.A.; Writing original draft: F.A. and M.W.; Writing review and editing: F.B.; Supervision: M.W. and W.A.T.; Project administration: F.B.

Ethical Statement: The research was conducted with integrity, fidelity, and honesty. The study was performed in accordance with ethical standards. The research did not involve any medical, clinical, or invasive procedures, and as such, formal ethical approval from an institutional review board was not deemed necessary.

All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors" as found in the Instructions for Authors.

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