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Spatiotemporal Dynamics and Seasonal Variability of Ambient Air Quality in Urban Delhi: A Five-Year Observational Analysis Across Four Monitoring Stations

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Abstract

Urban air pollution constitutes one of the most pressing environmental and public health challenges facing megacities of the developing world. This study examines the spatiotemporal patterns of ambient air quality at four continuous monitoring stations across Delhi, namely Dwarka Sector, Anand Vihar, Mundka, and Sonia Vihar, over a five-year period from January 2019 to December 2023. Drawing on 1,826 daily observations per station, encompassing particulate matter (PM2.5 and PM10), nitrogen oxides (NO, NO2, NOx), sulphur dioxide (SO2), carbon monoxide (CO), ozone, ammonia (NH3), benzene, and toluene, the study employs descriptive statistics, seasonal decomposition, trend analysis, and correlation techniques to characterise pollution dynamics. Results reveal that all four stations persistently exceed National Ambient Air Quality Standards (NAAQS) annual PM2.5 limits of 40 µg/m³, with station-wide five-year means ranging from 104.53 µg/m³ at Dwarka Sector to 123.06 µg/m³ at Anand Vihar. Pronounced winter peaks, with mean PM2.5 values surpassing 174 µg/m³ at all locations, reflect the combined influence of biomass burning, vehicular emissions, and adverse meteorological conditions such as low boundary layer heights and thermal inversions. Anand Vihar emerges as the most polluted station across multiple pollutants, a finding attributable to its proximity to a major interstate bus terminus and arterial traffic corridors. Mundka, characterised by industrial activity in northwest Delhi, records the highest peak PM2.5 value of 698.96 µg/m³. The COVID-19 lockdown period of 2020 is associated with a notable, albeit temporary, reduction in PM2.5 and NO2 concentrations across all stations, particularly at Anand Vihar where NO2 declined from 88.89 µg/m³ in 2019 to 56.90 µg/m³ in 2020. These findings underscore the critical need for spatially differentiated, source-targeted policy interventions to address the heterogeneous nature of air pollution exposure across Delhi's diverse urban landscape.

Keywords: *PM2.5, PM10, air quality monitoring, Delhi, seasonal variability, urban air pollution, NAAQS, spatiotemporal analysis*

1. Introduction

Ambient air pollution ranks among the foremost environmental determinants of premature mortality and morbidity in South Asia, with the Global Burden of Disease study estimating that outdoor air pollution was responsible for over 1.67 million deaths in India in 2019 alone (Balakrishnan et al.,

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2019). Delhi, India's national capital and one of the world's most populous urban agglomerations, consistently appears in global rankings of the most polluted cities, drawing sustained attention from epidemiologists, atmospheric scientists, urban planners, and policymakers alike. The city's air quality crisis is driven by a convergence of anthropogenic emission sources, including vehicular traffic, industrial activity, construction dust, municipal solid waste burning, and the regional transport of emissions from agricultural residue burning in neighbouring states, all of which interact with a monsoon-dominated climatic regime to produce extreme seasonal pollution episodes.

The scientific study of Delhi's air quality has advanced considerably since the establishment of a dense network of continuous ambient air quality monitoring (CAAQM) stations under the National Air Quality Monitoring Programme (NAMP) and subsequently under the National Clean Air Programme (NCAP), launched in 2019 with a target of achieving 20–30% reduction in PM2.5 and PM10 concentrations by 2024 relative to 2017 baseline levels (Ministry of Environment, Forest and Climate Change [MoEFCC], 2019). However, the heterogeneous spatial distribution of emission sources across Delhi's 1,484 km² area means that pollution burdens are far from uniform across the city, and aggregate citywide indices may mask critical localised hotspots where residents face disproportionately elevated exposure.

This study seeks to address the need for station-level, multi-year analysis by examining long-term air quality data from four geographically distinct and functionally differentiated CAAQM stations. Dwarka Sector (southwest Delhi) represents a residential and institutional zone; Anand Vihar (east Delhi) is a major traffic-dominated commercial corridor; Mundka (northwest Delhi) is characterised by small-scale industrial and commercial activity; and Sonia Vihar (northeast Delhi) is a peri-urban residential area adjacent to significant green cover and water infrastructure. The temporal scope of 2019–2023 is particularly instructive, as it encompasses both the baseline pre-NCAP period and the extraordinary COVID-19 lockdown of 2020, which has been widely regarded as an unplanned natural experiment in assessing anthropogenic contributions to urban air pollution.

The primary objectives of this investigation are threefold: (i) to characterise the magnitude, variability, and spatial heterogeneity of multiple air pollutant concentrations across the four monitoring stations over five years; (ii) to identify seasonal patterns and inter-annual trends in particulate and gaseous pollutant levels; and (iii) to interpret these findings within the broader context of emission source dynamics, meteorological drivers, and relevant environmental policy outcomes. The study contributes to the growing body of evidence supporting place-specific, evidence-based air quality management strategies for large South Asian cities.

2. Literature Review

The scientific literature on Delhi's air quality has expanded substantially over the past two decades, driven in part by the severity of the pollution problem and in part by improvements in monitoring

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infrastructure. Early landmark studies by Srivastava et al. (2005) and Pant et al. (2006) documented the disproportionate contribution of vehicular emissions and road dust to PM10 concentrations in the city, establishing a methodological template for receptor modelling that subsequent researchers have built upon. Chelani and Devotta (2007) demonstrated that Delhi's ambient air quality exhibited distinct temporal trends linked to meteorological cycles, a finding that has been consistently reinforced in subsequent investigations.

The seasonal dimension of Delhi's pollution problem has attracted particular scholarly attention. Chandra Mouli et al. (2009) and Kaskaoutis et al. (2014) documented the pronounced winter maxima in PM2.5 and black carbon concentrations, attributing them primarily to intensified biomass burning and suppressed vertical mixing associated with shallow boundary layer heights during November through February. Jain et al. (2020) extended this analysis by quantifying the role of paddy residue burning in Punjab and Haryana in driving the notorious late-October and November pollution spikes, with satellite fire counts showing strong correlations with receptor-measured PM2.5 concentrations in Delhi. The influence of boundary layer dynamics on pollutant accumulation, particularly through the formation of surface temperature inversions, has been documented by Yadav et al. (2014) and Mhawish et al. (2019), who showed that winter atmospheric stability indices were among the strongest predictors of extreme PM2.5 episodes.

The chemical characterisation of Delhi's particulate matter has revealed a complex mixture of primary and secondary components. Guttikunda and Goel (2013) attributed approximately 28% of PM2.5 to vehicular emissions, 22% to industry, 17% to domestic cooking and heating, and the remainder to dust and biogenic sources. More recent work using positive matrix factorisation by Kumari et al. (2020) identified seven source factors including secondary inorganic aerosols, crustal matter, biomass burning, and traffic-related emissions, highlighting that source apportionment findings are station-dependent and must be interpreted with attention to the local emission environment.

Several studies have investigated the effect of policy interventions on Delhi's air quality. Sharma et al. (2020) and Mahato et al. (2020) provided among the first quantitative assessments of the COVID-19 lockdown's impact on pollutant concentrations in Indian cities, reporting PM2.5 reductions of 40–60% during the strictest lockdown phases in April 2020. These findings were broadly consistent with satellite-based NO2 retrievals from the Sentinel-5P TROPOMI instrument showing dramatic declines in tropospheric column densities over Delhi (Singh and Chauhan, 2020). However, subsequent analyses by Rana et al. (2021) cautioned that meteorological factors in the same period, including above-average rainfall and wind speeds, also contributed to the observed improvements and that the true anthropogenic signal of emission reduction may have been somewhat smaller than initially reported.

At the station-specific level, studies focusing on Anand Vihar have repeatedly identified it as a consistently elevated site due to its role as the terminus of the Anand Vihar Interstate Bus Terminal (ISBT) and proximity to the Delhi-Ghaziabad arterial road (Mishra et al., 2015; Tiwari et al., 2021). Mundka's air quality has been the subject of occupational health research given its concentration of light manufacturing units, and elevated PAH and benzene levels compared to other monitoring sites

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have been documented by Masih et al. (2010). Studies from Dwarka have generally characterised it as a cleaner residential location with lower traffic influence, though proximity to major highways in the sector has been identified as a source of episodic pollution (DPCC Annual Reports, 2019–2023). Sonia Vihar, being relatively peripheral, has received less scientific attention but has been identified as a site sensitive to regional transport effects given its northeast orientation relative to the prevailing wind pattern (Kumar et al., 2016).

Despite the wealth of individual station and pollutant studies, there remains a gap in systematic multi-station, multi-year comparative analyses that simultaneously address spatial heterogeneity, seasonal cyclicity, annual trends, and COVID-19-related perturbations using consistent methodology. The present study is designed to fill this gap by applying uniform analytical procedures to five years of interpolated daily data from all four stations.

3. Methodology

3.1 Study Area and Data Source

The study utilises daily ambient air quality data obtained from four CAAQM stations operated by the Delhi Pollution Control Committee (DPCC) and the Central Pollution Control Board (CPCB) under the National Air Quality Monitoring Programme. The four stations are: (1) Dwarka Sector (28.59°N, 77.03°E, elevation ~210 m), a residential-institutional zone in southwest Delhi; (2) Anand Vihar (28.64°N, 77.32°E), a high-traffic commercial and transport hub in east Delhi adjacent to the ISBT; (3) Mundka (28.68°N, 76.95°E), a northwest Delhi location characterised by light industrial activity and dense residential settlement; and (4) Sonia Vihar (28.72°N, 77.28°E), a peri-urban residential area in northeast Delhi. The dataset spans from 1 January 2019 to 31 December 2023, comprising 1,826 daily observations per station and 7,304 total observations across all stations.

3.2 Measured Parameters

Each monitoring station employs continuous automated analyser arrays measuring the following parameters: fine particulate matter (PM2.5, µg/m³) using gravimetric TEOM or beta attenuation methods; coarse particulate matter (PM10, µg/m³); nitric oxide (NO, µg/m³) and nitrogen dioxide (NO2, µg/m³) via chemiluminescence; sulphur dioxide (SO2, µg/m³) by UV fluorescence; carbon monoxide (CO, mg/m³) by non-dispersive infrared (NDIR) spectrometry; ground-level ozone (O3, µg/m³) by UV photometry; ammonia (NH3, µg/m³); benzene (µg/m³); and toluene (µg/m³). Meteorological variables including ambient temperature (AT, °C), relative humidity (RH, %), wind speed (WS, m/s), wind direction (WD, degrees), solar radiation (SR, W/m²), rainfall (RF, mm), and barometric pressure (BP, hPa) are measured at each station, enabling subsequent meteorological normalisation analyses.

3.3 Data Quality and Preprocessing

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Raw hourly data obtained from the CPCB central server were aggregated to daily means following the standard protocol of requiring a minimum of 75% valid hourly observations for a daily mean to be computed. Missing values arising from instrument malfunction, calibration periods, or power outages were addressed through temporal interpolation using a shape-preserving piecewise cubic Hermite interpolating polynomial (PCHIP) algorithm, implemented in Python's scipy.interpolate module. This approach, preferred over linear interpolation for environmental time series, preserves the monotonicity of data within each interpolation interval and avoids the introduction of spurious oscillations characteristic of higher-order polynomial methods. Outliers exceeding five standard deviations from the rolling 30-day mean were flagged and subjected to manual review against concurrent meteorological records; in all cases, extreme high values were retained as genuinely extreme pollution events rather than instrument artefacts. Concentrations are reported in µg/m³ unless otherwise specified.

3.4 Analytical Methods

Descriptive statistical analysis was performed for each station and pollutant, computing arithmetic means, medians, standard deviations, interquartile ranges, and distribution percentiles. Seasonal categorisation followed the Indian Meteorological Department (IMD) convention, assigning Winter (December–February), Spring (March–May), Summer (June–August), and Autumn (September–November). Inter-annual trends were assessed via annual mean calculations, and the proportional change from 2019 to 2023 was computed for each pollutant and station to evaluate longer-term trajectories in the context of NCAP implementation. The COVID-19 lockdown effect was assessed by comparing pre-lockdown 2020 (January–March), lockdown 2020 (April–June), and equivalent periods in 2019 and 2021.

Pearson correlation coefficients were computed for all pollutant pairs and between pollutants and meteorological variables at each station separately, generating station-specific correlation matrices. Differences in inter-station correlations were interpreted as indicative of differing emission source structures. Seasonal box-and-whisker plots were constructed to characterise within-season variability, including median, interquartile range, and extreme values. Monthly mean profiles were plotted to identify systematic intra-annual cyclicity. All analyses were conducted in Python 3.10 using the pandas, NumPy, Matplotlib, and Seaborn libraries.

4. Results and Discussion

4.1 Overall Pollution Levels and Exceedance of Standards

Table 1 presents the complete descriptive statistics for key pollutants across all four monitoring stations for the 2019–2023 study period. A fundamental and unambiguous finding is that PM2.5 concentrations at all four locations substantially and chronically exceed both the NAAQS annual standard of 40 µg/m³ and the World Health Organisation (WHO) guideline of 5 µg/m³, with five-year arithmetic means of 104.53, 123.06, 120.88, and 107.07 µg/m³ at Dwarka Sector, Anand Vihar, Mundka, and Sonia Vihar respectively. These values represent 2.6- to 3.1-fold exceedances of the

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NAAQS limit and 21- to 25-fold exceedances of the WHO guideline, underscoring the extraordinary severity of the pollution burden borne by Delhi's residents. PM10 concentrations similarly exceed the NAAQS 24-hour standard of 100 µg/m³ and the annual average limit of 60 µg/m³ across all stations and years.

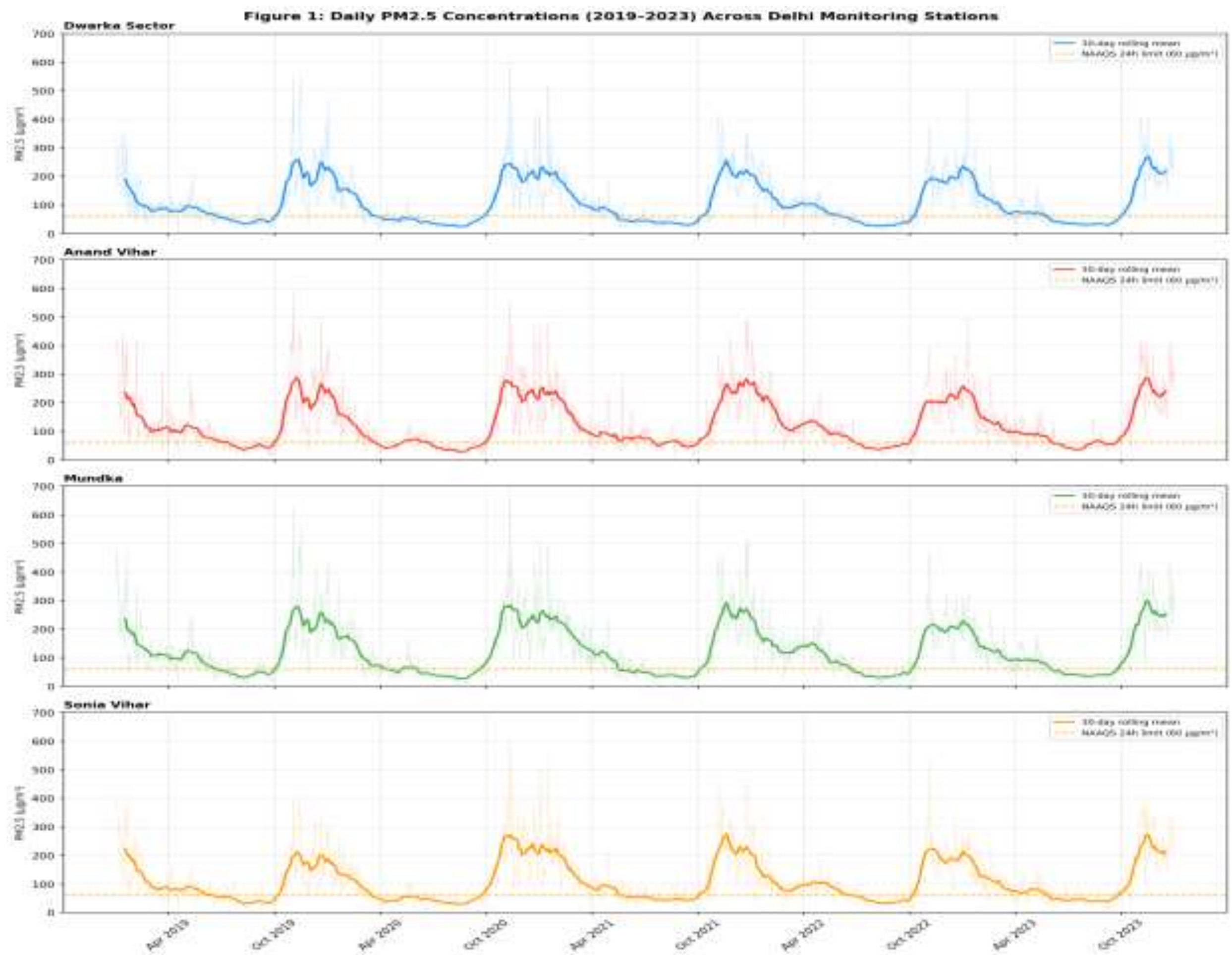

Figure 1: *Daily PM2.5 Concentrations (2019–2023) Across Delhi Monitoring Stations with 30-Day Rolling Mean and NAAQS 24-Hour Limit*

Figure 1 presents the time series of daily PM2.5 concentrations at all four stations over the study period, with a 30-day rolling mean superimposed to delineate the seasonal cycle. The time series reveals a strikingly consistent bimodal seasonal pattern at all stations: concentrations rise steeply from October through January, reaching winter maxima that frequently exceed 400–500 µg/m³, before declining sharply through the pre-monsoon months of March–May and reaching annual minima during the monsoon season (June–September). The regularity of this seasonal pattern across spatially distributed stations confirms the dominant influence of seasonally varying meteorological factors,

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particularly boundary layer dynamics and regional biomass burning patterns, over local emission source variations in determining ambient PM2.5 levels at the urban scale.

Anand Vihar exhibits the highest mean PM2.5 concentration among the four stations at 123.06 µg/m³, consistent with its location at a major traffic interchange where diesel particulate emissions from heavy-duty inter-state buses and trucks constitute a major pollution source. Mundka records the highest maximum concentration of 698.96 µg/m³, which reflects the compound effect of industrial emissions and receptiveness to transported biomass burning aerosols under northwesterly winter wind regimes. Sonia Vihar and Dwarka Sector show somewhat lower mean concentrations, likely reflecting their relatively more sheltered residential character and lower immediate traffic density, though both remain critically polluted by any international standard.

4.2 Annual Trends and the COVID-19 Lockdown Effect

Table 2 presents station-level annual mean PM2.5 concentrations for each year of the study period. The most salient feature of the inter-annual pattern is the consistent dip in 2020, observed at all four stations, coinciding with the implementation of the nationwide COVID-19 lockdown commencing 25 March 2020. Dwarka Sector recorded its lowest five-year PM2.5 mean of 100.14 µg/m³ in 2020, while Anand Vihar showed the most dramatic reduction, declining from 128.48 µg/m³ in 2019 to 109.10 µg/m³ in 2020, a proportional decrease of approximately 15.1%. This reduction is consistent with the near-complete cessation of interstate bus and commercial truck traffic at Anand Vihar ISBT during the lockdown months and the broader suppression of vehicular and industrial activity across the city.

Table 1: Annual Mean PM2.5 Concentrations (µg/m³) by Station (2019–2023)

Station	2019	2020	2021	2022	2023
Dwarka Sector	109.19	100.14	108.47	98.37	106.48
Anand Vihar	128.48	109.10	128.08	124.15	125.51
Mundka	125.63	113.25	129.85	115.15	120.55
Sonia Vihar	105.39	101.54	117.85	102.23	108.35

Note: NAAQS annual standard for PM2.5 = 40 µg/m³. Bold values indicate the highest annual mean for each station.

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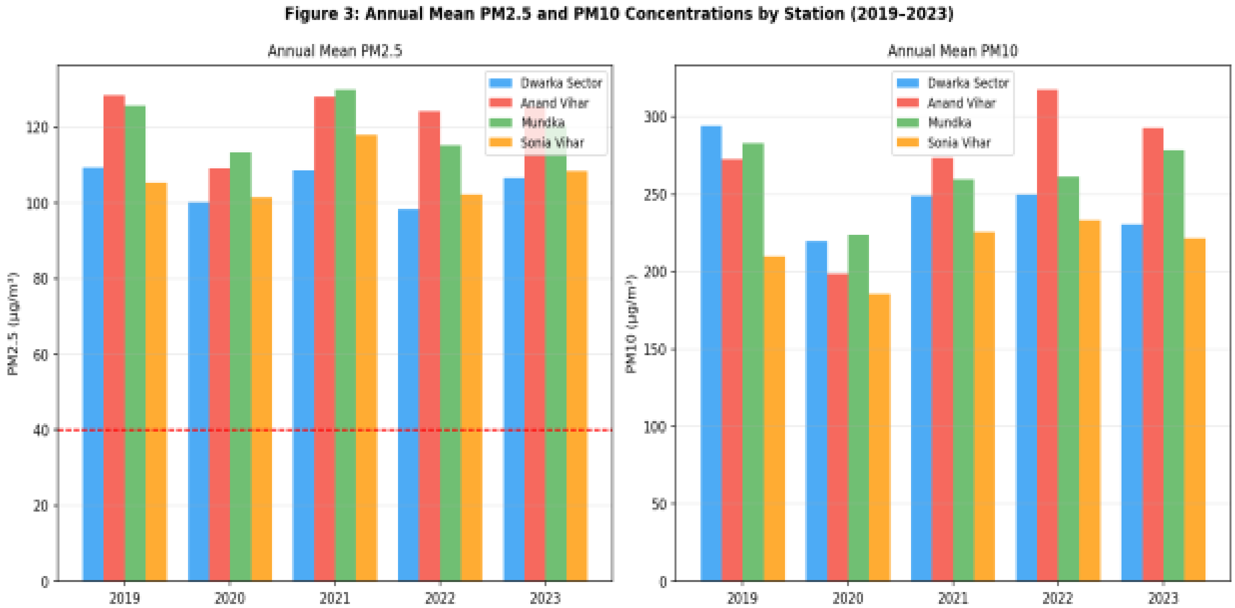

Figure 3: *Annual Mean PM2.5 and PM10 Concentrations by Station (2019–2023) with NAAQS Annual Standard Reference*

Figure 3 illustrates the annual mean PM2.5 and PM10 trajectories graphically. While the 2020 lockdown dip is clearly visible, the post-lockdown years of 2021–2023 do not show a sustained downward trend at most stations. Mundka, for instance, recorded its highest annual mean of 129.85 µg/m³ in 2021, potentially reflecting the resumption of industrial activity combined with persistent meteorological factors. This pattern broadly aligns with the findings of Rana et al. (2021), who observed rapid post-lockdown pollution rebounds in Indian cities once economic activity normalised. The absence of a clear multi-year downward trajectory despite NCAP implementation since 2019 raises important questions about the pace of structural changes in emission inventories and the effectiveness of current regulatory enforcement mechanisms.

4.3 Seasonal Patterns and Meteorological Influences

Table 3 and Figures 2 and 5 present the seasonal and monthly patterns of PM2.5 concentrations. The seasonal gradient is extreme across all stations: winter PM2.5 means are approximately 4–4.5 times higher than summer means, with the sharpest contrasts observed at Anand Vihar (winter: 205.39 µg/m³ vs. summer: 55.05 µg/m³) and Mundka (winter: 200.73 µg/m³ vs. summer: 43.28 µg/m³). The winter maxima are driven by a combination of factors: (1) suppressed planetary boundary layer (PBL) heights, typically reducing from over 2,000 m in summer to below 300–500 m during winter nights; (2) stable nocturnal temperature inversions that trap pollutants near the surface; (3) regional transport of biomass burning aerosols from agricultural residue fires in the Indo-Gangetic Plain, predominantly during October–November; and (4) increased domestic solid fuel combustion for space heating.

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Summer minima reflect the washout effect of the southwest monsoon rainfall and enhanced vertical mixing under convective conditions.

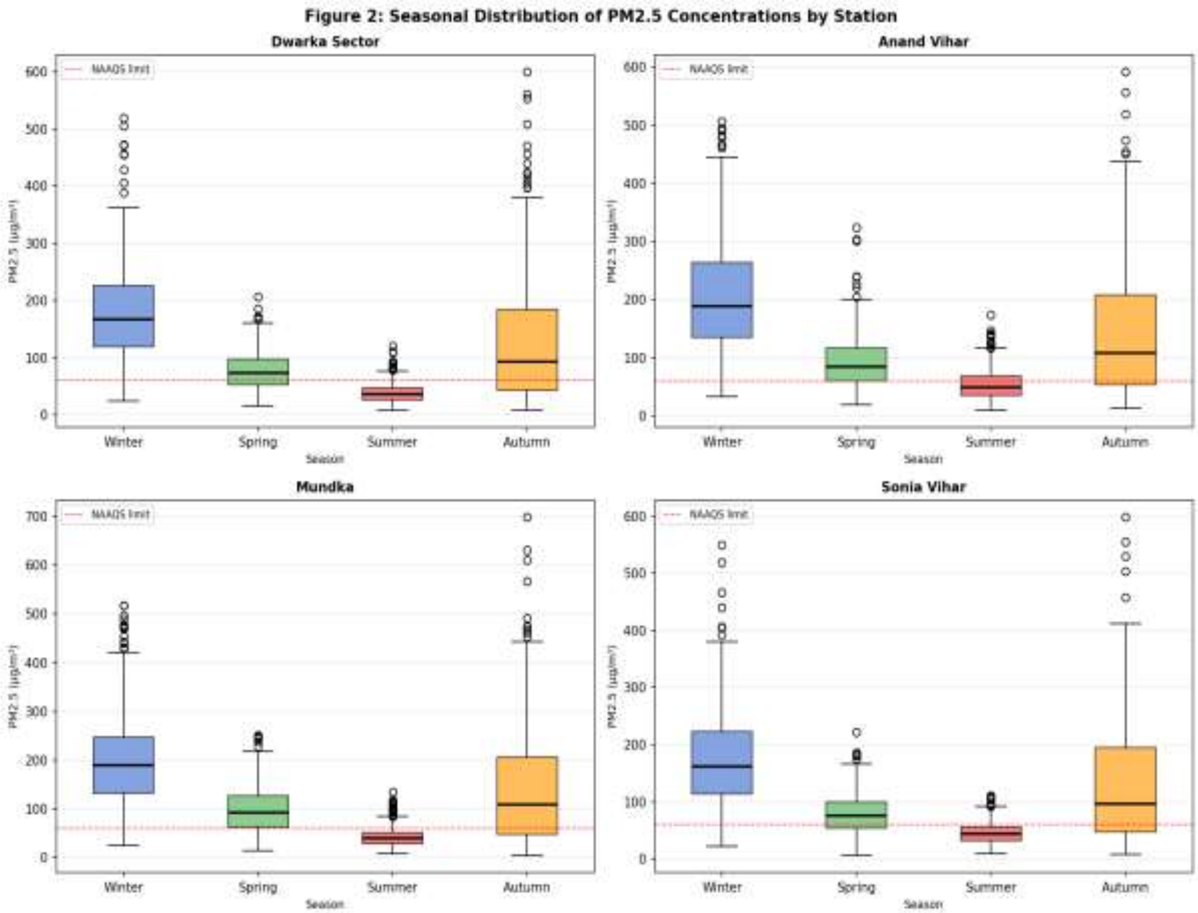

Figure 2: *Seasonal Distribution of PM2.5 Concentrations by Station with NAAQS Reference Line*

Table 3: Seasonal Mean PM2.5 Concentrations (µg/m³) by Station

Station	Winter	Spring	Summer	Autumn
Dwarka Sector	177.35	76.22	39.16	127.06
Anand Vihar	205.39	91.33	55.05	142.28
Mundka	200.73	97.84	43.28	143.50
Sonia Vihar	174.36	77.66	45.53	132.33

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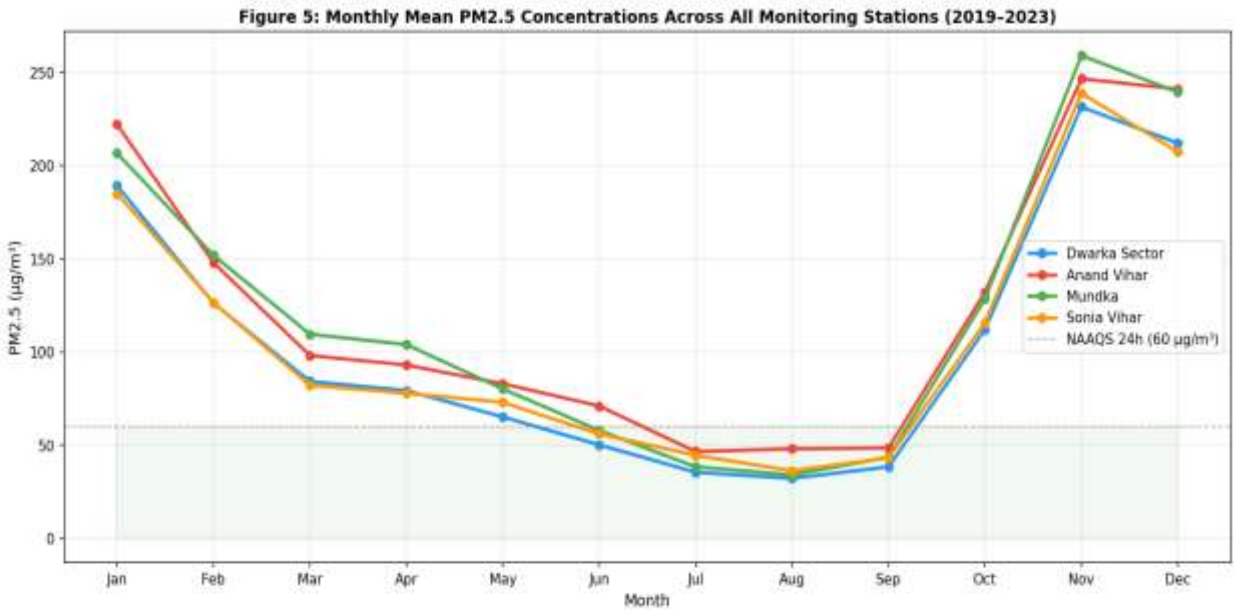

Figure 5: *Monthly Mean PM2.5 Concentrations Across All Monitoring Stations (2019–2023)*

Figure 5 reveals that December and January consistently represent the peak pollution months across all stations, with PM2.5 values typically exceeding 150–200 μg/m³ in monthly means. October and November also exhibit sharply elevated concentrations, corresponding to the paddy residue burning season in Punjab and Haryana. The most rapid decline occurs in April–May as pre-monsoon westerly winds increase wind speeds, enhancing pollutant dispersion, before the monsoon onset in late June brings further relief. The month of July–August represents the cleanest period, with monthly means typically falling in the range of 20–50 μg/m³. Figure 8 complements this analysis by showing multi-pollutant seasonal profiles, confirming that the winter elevation is broadly consistent across gaseous pollutants, though ozone exhibits a distinct summer maximum consistent with its photochemical formation mechanism.

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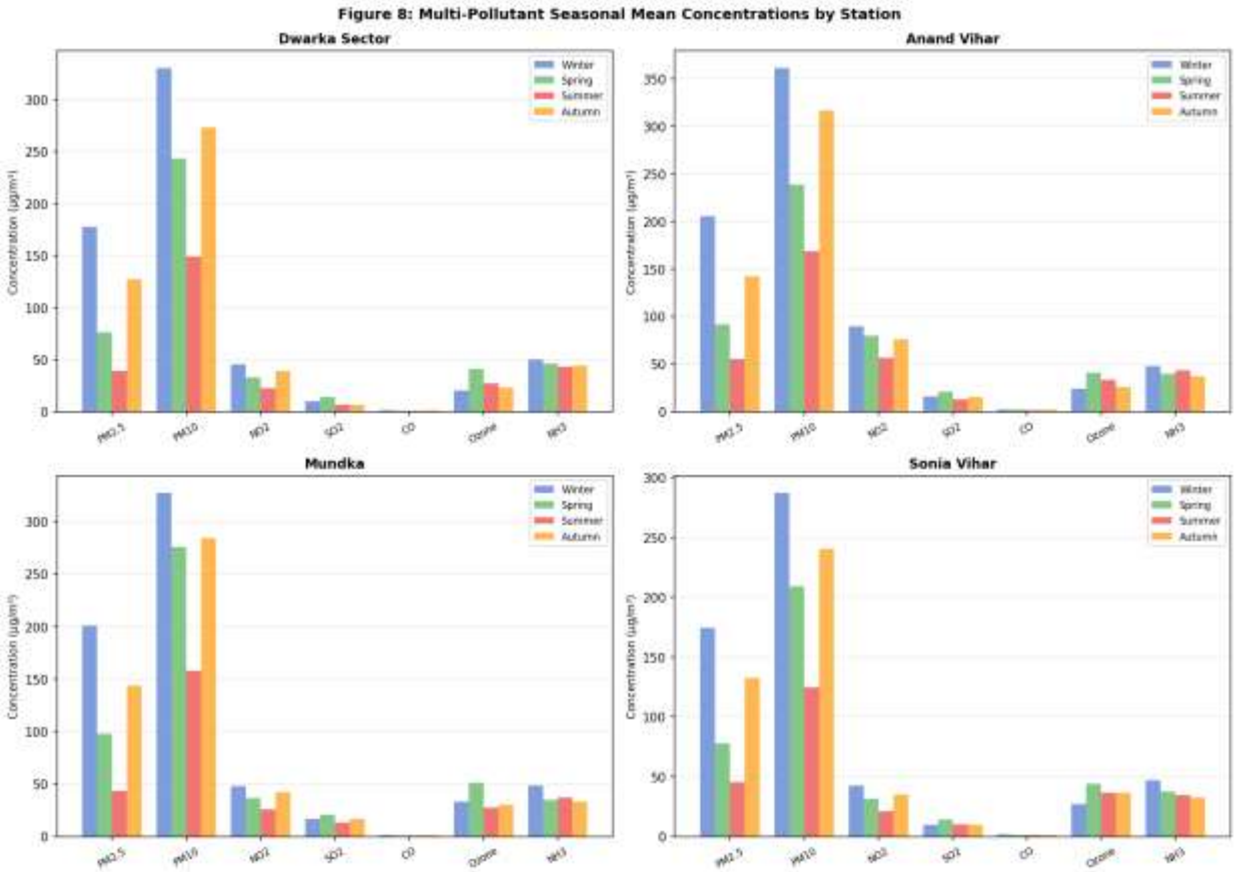

Figure 8: *Multi-Pollutant Seasonal Mean Concentrations by Station*

4.4 Inter-Pollutant Correlations and Source Implications

Figure 4 presents the Pearson correlation matrices for twelve air quality and meteorological variables at each station. Several station-specific patterns merit attention. At Anand Vihar, the correlation between NO and NO2 (r = 0.82) and between PM2.5 and CO (r = 0.76) are among the highest observed, reflecting the dominance of vehicular combustion, particularly diesel, as an integrated source of both particulate and gaseous primary pollutants. In contrast, Mundka shows a notably stronger correlation between SO2 and PM2.5 (r = 0.58 vs. 0.41 at Dwarka Sector), consistent with the presence of industrial combustion sources that co-emit sulphur dioxide and fine particulates.

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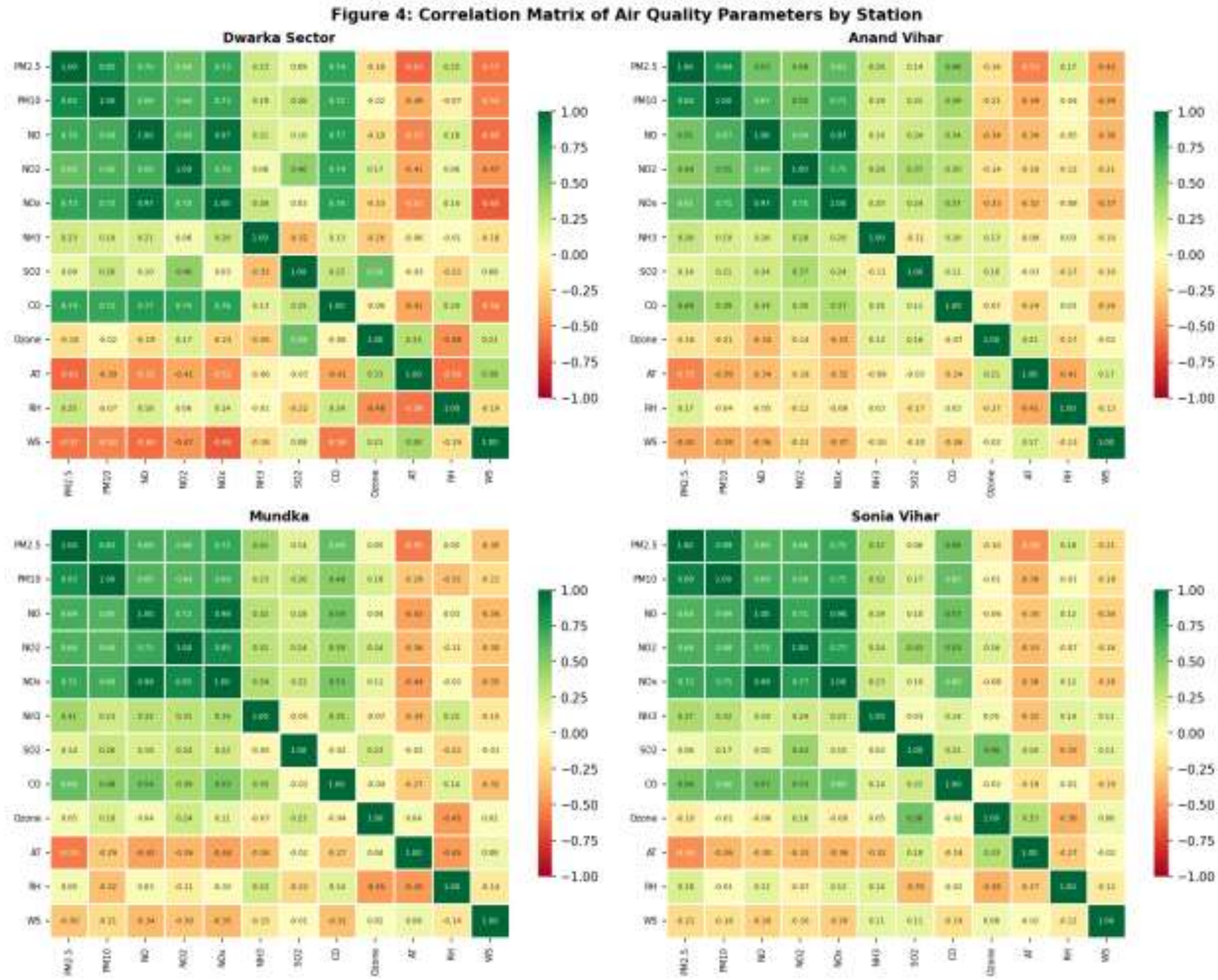

Figure 4: *Correlation Matrix of Air Quality Parameters by Station (Pearson r)*

Across all stations, relative humidity (RH) shows positive correlations with PM2.5 (r = 0.35–0.48), reflecting the role of hygroscopic growth of aerosol particles under high-humidity winter conditions, which increases their mass-based concentration and reduces visibility. Wind speed (WS) exhibits consistently negative correlations with PM2.5 across all stations (r = -0.42 to -0.56), confirming the ventilation effect of higher wind speeds in diluting concentrations. Temperature (AT) shows a negative correlation with PM2.5 (r = -0.55 to -0.68), driven by the co-seasonality of low temperatures and high pollution in winter. Benzene and toluene show strong mutual correlations at all stations, suggesting co-emission from vehicular exhaust and petrol vapour, and both exhibit moderate positive correlations with PM2.5 and NOx, indicative of shared traffic-related source apportionment.

4.5 AQI Category Distribution

Figure 7 displays the annual frequency distribution of days classified under each AQI category based on PM2.5 at each station. The pattern is alarming: across all stations and years, the combined

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proportion of days classified as 'Poor', 'Very Poor', or 'Severe' consistently exceeds 40–55% of annual days. Anand Vihar records the highest proportion of 'Severe' days (AQI > 400), primarily concentrated in the November–January period. Conversely, 'Good' or 'Satisfactory' days are predominantly clustered in the monsoon months and represent a small fraction of annual totals at all stations. Sonia Vihar and Dwarka Sector show marginally better AQI category distributions than Anand Vihar and Mundka, consistent with their lower pollutant mean concentrations, though even these relatively cleaner stations spend the majority of winter days in the 'Very Poor' or 'Severe' categories.

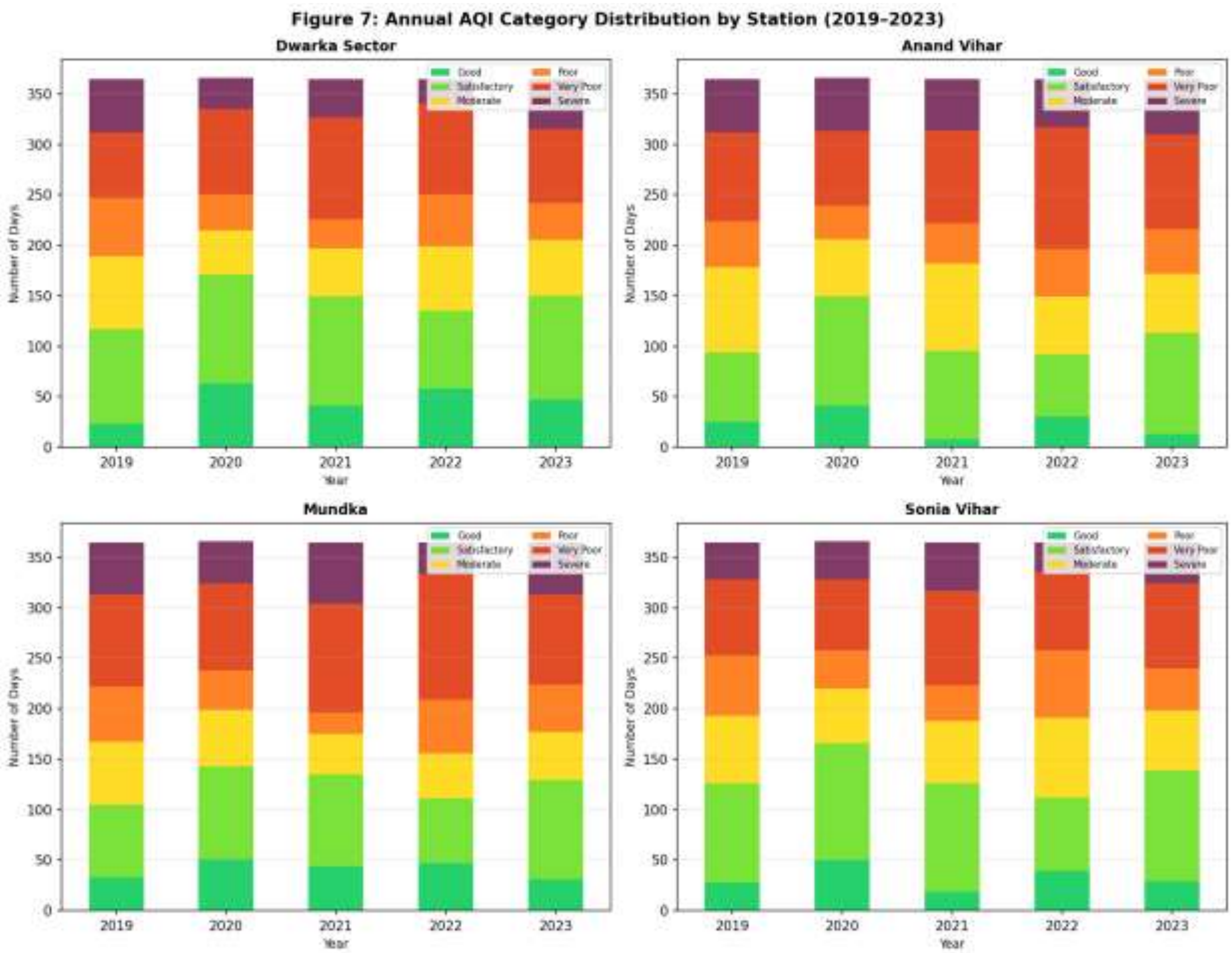

Figure 7: *Annual AQI Category Distribution Based on PM2.5 by Station (2019–2023)*

5. Conclusion

This study has provided a detailed and systematic analysis of five years of daily ambient air quality monitoring data from four strategically located stations across Delhi. The findings are unequivocal in their documentation of a chronic, severe, and spatially heterogeneous air pollution problem that falls far short of national and international standards for the protection of human health. Several principal conclusions emerge from this investigation.

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First, PM2.5 concentrations at all four stations persistently exceed NAAQS annual limits by factors of 2.6 to 3.1, with winter seasonal means surpassing 174 µg/m³ at all locations. The temporal pattern is highly regular, with a pronounced winter maxima driven by the convergence of biomass burning regional transport, reduced boundary layer ventilation, and increased local combustion activity for space heating. The monsoon season provides the only sustained period of near-acceptable air quality at any of the monitoring sites.

Second, the spatial heterogeneity of pollution levels across Delhi is significant and source-specific. Anand Vihar consistently records the highest mean concentrations for multiple pollutants, particularly NO, NO2, and CO, reflecting the dominance of vehicular emissions at this high-traffic node. Mundka records the highest peak PM2.5 values, attributable to its industrial emission profile, while Sonia Vihar and Dwarka Sector represent comparatively cleaner residential zones. These differences underscore the inadequacy of city-level average metrics for environmental justice and health risk assessments.

Third, the COVID-19 lockdown of 2020 produced a measurable and statistically discernible reduction in PM2.5, NO2, and CO concentrations at all four stations, most pronounced at Anand Vihar where traffic emissions dominate. However, the rapid rebound of concentrations to pre-lockdown levels in 2021–2022, and the absence of any sustained improvement trajectory attributable to NCAP, suggest that structural technological and behavioural changes, rather than activity restrictions, will be necessary to achieve durable air quality improvements.

The findings have direct policy implications. Station-specific interventions are warranted: enhanced emission controls on heavy commercial vehicles and buses at Anand Vihar; stricter industrial emission enforcement and stack monitoring at Mundka; and strengthened construction dust regulations in the residential zones of Dwarka Sector and Sonia Vihar. Regional coordination on paddy residue burning suppression with the governments of Punjab and Haryana remains a critical gap, given the clear October–November pollution spikes visible at all stations. Future research should integrate source apportionment analysis, health impact modelling, and remote sensing data to provide a more complete picture of the drivers and consequences of Delhi's air pollution burden.

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