OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Seasonal Variation in Air Quality Across Four Regions of Delhi: An Analysis of CPCB Data

Aastha Sharma[1]
[1]aastha200926@gmail.com

ABSTRACT

Delhi's air pollution shows high spatial and seasonal variation due to changes in emission sources and atmospheric conditions. The present study has evaluated the seasonal variation of air quality parameters for four monitoring stations of the Central Pollution Control Board (CPCB), namely Anand Vihar, Sector-8, Dwarka, Jahangirpuri, and R. K. Puram during the period of March 2025 to February 2026. The mean concentrations of $PM_{2.5}$, PM_{10}, NO, NO_2, NH_3, SO_2, CO, O_3 and benzene were computed and compared between summer, monsoon and winter. The highest particulate pollution was observed in winter and the lowest during monsoon. The mean $PM_{2.5}$ level rose from 66.27 µg/m³ in the monsoon season to 211.28 µg/m³ in winter, which is 218.8% higher. Similarly, mean PM_{10} increased from 156.53 to 342.27 µg/m³, corresponding to a 118.7% rise. The top pollution affected area in summer was Jahangirpuri, and in winter it was Anand Vihar, while the highest $PM_{2.5}$ concentration was at Jahangirpuri and the highest PM_{10} concentration was at Anand Vihar. The maximum mean values of most gaseous pollutants occurred in winter, whereas ozone peaked in summer, unlike most primary pollutants, likely due to stronger photochemical production. The results reveal substantial seasonal and spatial variations in pollution levels in Delhi, highlighting the severity of the situation during the winter season. These findings highlight the importance of location-specific and seasonally responsive air-quality interventions, especially at locations that are influenced by traffic and industry.

Keywords: *air pollution; CPCB; Delhi; particulate matter; seasonal variation; spatial variation*

1. INTRODUCTION

Despite the improvement in the number of days with good air quality at the national capital Delhi, air pollution still poses a significant environmental and public health threat. Delhi had an annual mean Air Quality Index (AQI) of 209 in 2024, and 157 days were ranked in the “poor” to “severe” AQI range, according to the Commission for Air Quality Management. The seasonal difference was also substantial, with August having a mean AQI of 72, November a mean AQI of 374, and January a mean AQI of 355 (Commission for Air Quality Management [CAQM] 2024). These statistics show that average figures can mask high pollution events in a year and also illustrate the importance of making assessments on a seasonal basis. Particulate matter and gaseous pollutants are linked to health impacts on respiratory and cardiovascular systems, and understanding seasonal trends is crucial for public-health protection and environmental management (World Health Organization [WHO], 2021).

The air quality in Delhi is affected by various factors such as vehicle emission, industrial/commercial combustion and emissions, road dust re-suspension, burning of waste and biomass, and regional transport of pollutants. The level of contribution from these sources is dependent on the type of land use, traffic density, population density, and location to emission sources within the city. Multi-year observations across the Delhi National Capital Region have shown significant spatial variations in the levels of PM and trace gases, and data from one monitoring station may not fully represent the situation across the city (Hama et al., 2020). The recent measurements of particulate matter, black carbon and metals have also shown that there is considerable variation between different locations in Delhi (Kumar et al., 2024). A multi-station approach is thus needed to detect high concentrations of pollutants at regular stations.

Accumulation and dispersion, transformation, and removal of air pollutants are influenced by seasonal meteorology. In winter, cold temperatures, light winds, shallow mixing layers and temperature inversions limit the vertical movement of pollutants and increase the likelihood of pollutants remaining in the lowest layer of the atmosphere. Pollutant dispersion is generally enhanced by increased atmospheric mixing, and wet scavenging during monsoon rains decreases particulate levels. Dry weather and strong winds can contribute to an increase in PM_{10} in the summer, while warm weather and increased sunlight can promote the formation of photochemical ozone. A review of the meteorological factors influencing Delhi indicated that temperature, relative humidity, wind speed, boundary-layer height, and rainfall had varying impacts on pollutants such as PM2.5 and SO2 based on seasons (Garsa et al., 2023).

Particulate-matter concentrations have often been found to be high during the post-monsoon and winter seasons and low during monsoon seasons in previous studies. Sharma et al. (2022) correlated the winter pollution in Delhi with the decrease in atmospheric ventilation and the unfavourable dispersion conditions. Also, using the CPCB observations between 2018 and 2022, Vaishali and Das (2025) identified clear differences in $PM_{2.5}$ concentrations between industrial/traffic sites and commercial/green sites, showing higher levels at industrial/traffic sites and lower levels at commercial/green sites. These results show how both seasonal meteorology and the local emission characteristics affect the pollution level.

The air pollution in Delhi is also multi-faceted as it is the result of interaction between primary emissions, atmospheric transport and secondary air pollutants. During heavy pollution events, the biomass burning sources were found to be significant contributors to PM, while the contribution from traffic and industrial sources was significant in the case of VOCs and secondary pollutant formation, as observed during measurements (Awasthi et al., 2024). In addition, not all pollutants are impacted equally by changes in human activity. When comparing air quality in 2019 with the COVID-19 year of 2020, Shankar and Gadi (2022) identified varied responses in the case of different pollutants. Thus, it is more useful to consider the situation for each pollutant than to only think in terms of a composite AQI.

Delhi has been studied in great detail, but a number of the studies are devoted to the study of particulate matter, individual pollution incidences, lockdowns, or to city-wide AQI values. There have not been many recent studies that have assessed seasonal variations in a wide variety of particulate, gaseous and organic pollutants at a large number of monitoring sites over a full year cycle. This should be done to check

whether the pollutants have similar seasonal variations and if these variations are consistent in various geographically separate zones of Delhi.

The first aim of this study was to evaluate the air quality for four monitoring sites in Delhi (Anand Vihar, Dwarka Sector 8, Jahangirpuri and R K Puram) based on the air quality data provided by CPCB from March 2025 to February 2026. Seasonal mean concentrations of $PM_{2.5}$, PM_{10}, nitric oxide, nitrogen dioxide, ammonia, sulfur dioxide, carbon monoxide, ozone, and benzene were calculated and compared across summer, monsoon and winter. The study further aimed to identify station-level differences, determine the pollutants and locations exhibiting the greatest seasonal increases, and quantify the changes in particulate-matter concentrations between seasons. The findings provide recent evidence on the seasonal and spatial distribution of air pollution in Delhi and may support the development of location-specific and seasonally responsive pollution-control measures.

2. METHODOLOGY

2.1. Study Design

This study used a quantitative, retrospective observational design to assess seasonal and spatial variations in ambient air-pollutant concentrations across four monitoring locations in Delhi. The analysis was based on secondary data obtained from the Central Pollution Control Board (CPCB). No field sampling or direct pollutant measurements were undertaken by the researchers.

2.2. Data Source and Study Locations

Air-quality data were obtained from the CPCB Central Control Room for Air Quality Management portal, which provides measurements recorded by Continuous Ambient Air Quality Monitoring Stations. The study period was from March 2025 to February 2026, which comprised the areas of Anand Vihar, Dwarka Sector 8, Jahangirpuri, and R.K. Puram. These stations were selected as they provided pollutant data during the study period, and they are representative of contrasting urban environments in Delhi.

2.3. Pollutants and Measurement Units

Particulate matter with an aerodynamic diameter of 2.5 µm or less ($PM_{2.5}$), 10 µm or less (PM_{10}), nitric oxide (NO), nitrogen dioxide (NO_2), ammonia (NH_3), sulphur dioxide (SO_2), carbon monoxide (CO), ozone (O_3), and benzene were included in the analysis. $PM_{2.5}$, PM_{10}, NO, NO_2, NH_3, SO_2, O_3, and benzene were expressed in $\mu g\ m^{-3}$, while CO was expressed in $mg\ m^{-3}$.

2.4. Seasonal Classification

The observations were categorized into three 4-month periods of seasons: summer (March-June 2025), monsoon (July-October 2025), and winter (November 2025-February 2026). All comparisons of pollutants and stations were made using these categories. These equal-duration periods provide a consistent four-month grouping across the annual cycle; the July–October category is an analytical grouping rather than a strict meteorological definition of monsoon. October was retained to preserve the original grouping, but it can represent a post-monsoon transition with higher pollution and may raise the

July–October mean. A sensitivity comparison using July–September as monsoon and treating October separately as post-monsoon could not be calculated from the seasonal summaries available for this revision; it requires monthly or daily observations and the corresponding valid-observation counts.

2.5. Data Preparation and Quality Control

The CPCB data were organized by monitoring station, pollutant, month, and season in Microsoft Excel. Observations reported as missing or unavailable were excluded, and no missing values were estimated or imputed. The number of valid monitoring days supplied with the dataset was retained to assess data availability. No additional outlier removal or adjustment was applied to valid CPCB observations. Differences in the number of valid observations, particularly for ozone and benzene, were considered during interpretation.

The exact valid-day counts by pollutant, station, and season are not reproduced in the available seasonal summaries. Consequently, data completeness cannot be quantified for each combination, and the potential effect of unequal coverage on seasonal comparisons remains a limitation.

2.6. Calculation and Comparison of Mean Concentrations

Seasonal mean concentrations were calculated separately for each pollutant at each monitoring station using all valid observations available within the corresponding seasonal period. Missing or unavailable observations were excluded from the calculations.

Station-level seasonal means were compared across summer, monsoon and winter to identify temporal patterns. Spatial variation was assessed by comparing the seasonal means of the four monitoring stations for the same pollutant. For the overall seasonal summaries, an unweighted arithmetic mean of the four station-level means was calculated, giving equal weight to each monitoring location.

The magnitude of seasonal change was assessed by calculating the percentage change in each pollutant's four-site mean concentration from monsoon to winter. Positive values indicated higher concentrations during winter. The analysis was descriptive, and no inferential statistical tests were conducted; therefore, the observed differences were not interpreted as statistically significant.

Spatial variability in particulate matter was additionally summarized as the minimum–maximum interval and its width (maximum minus minimum) across the four station-level seasonal means in Table 2. These measures describe between-station variability, not day-to-day variability. Within-station seasonal standard deviations, medians, and interquartile ranges cannot be derived from seasonal means alone and were not calculated without the underlying observations.

2.7. Ethical Issues

The study employed publicly available aggregated data from environmental monitoring provided by the CPCB website. There were no individual persons, animals, personal identifiers, confidential records, or

individually identifiable information in the dataset. Therefore, informed consent and approval from a human-research ethics committee were not required.

The data were used for academic research only, and the published data did not result in the alteration or selective misrepresentation of the available measurements. The missing observations were not estimated but were excluded transparently, and CPCB was credited as the source of data. Data collection, manipulation, and interpretation were performed with care for correctness, proper attribution, and responsible use of public information from government agencies.

3. RESULTS

3.1. Overview of seasonal pollutant concentrations

Seasonal mean concentrations were summarized for Anand Vihar, Dwarka Sector 8, Jahangirpuri, and R.K. Puram. The four-site means reported here are unweighted arithmetic means of the corresponding station-level seasonal concentrations. Because the number of valid monitoring days differed among some station-pollutant-season combinations, the comparisons are descriptive and do not imply statistical significance.

Particulate matter displayed the largest seasonal contrast. The four-site mean $PM_{2.5}$ concentration was 66.27 µg m^{-3} during monsoon, 75.86 µg m^{-3} during summer, and 211.28 µg m^{-3} during winter. The corresponding PM_{10} concentrations were 156.53, 205.55, and 342.27 µg m^{-3}, respectively (Table 1; Figure 1). Relative to monsoon, winter $PM_{2.5}$ increased by 218.8%, whereas winter PM_{10} increased by 118.7%.

Table 1. Four-site seasonal mean concentrations of the measured air pollutants

Pollutant	Unit	Monsoon	Summer	Winter
$PM_{2.5}$	µg m^{-3}	66.27	75.86	211.27
PM_{10}	µg m^{-3}	156.53	205.55	342.27
NO	µg m^{-3}	25.50	16.94	61.98
NO_2	µg m^{-3}	34.58	40.77	73.86
NH_3	µg m^{-3}	23.86	42.31	55.58
SO_2	µg m^{-3}	15.30	17.11	23.84

Pollutant	Unit	Monsoon	Summer	Winter
O_3	µg m^{-3}	26.79	42.02	27.14
Benzene	µg m^{-3}	1.31	0.71	3.37
CO	mg m^{-3}	0.72	0.68	1.81

Note. Values are unweighted arithmetic means of the four station-level seasonal concentrations. CO is reported in mg m^{-3}; all other pollutants are reported in µg m^{-3}.

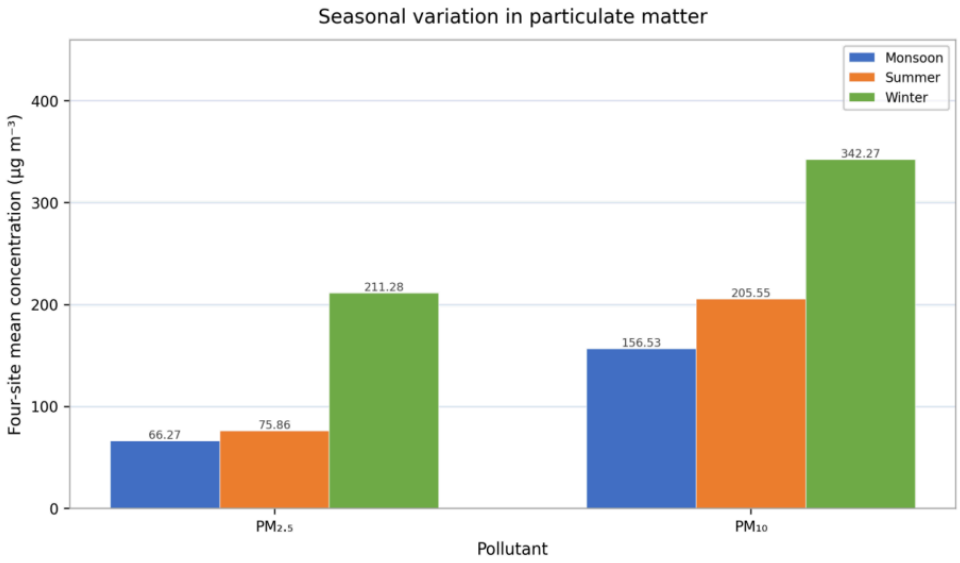


Figure 1. Four-site seasonal mean concentrations of $PM_{2.5}$ and PM_{10}. Values are based on the station-level seasonal means reported in the source dataset.

3.2. Spatial patterns in particulate matter

Spatial differences were present in each season (Table 2; Figure 2). During monsoon, $PM_{2.5}$ ranged from 51.82 µg m^{-3} at Dwarka Sector 8 to 81.39 µg m^{-3} at Jahangirpuri. During summer, it ranged from 69.99 µg m^{-3} at R.K. Puram to 86.54 µg m^{-3} at Jahangirpuri. Winter concentrations increased at all four sites and ranged from 187.81 µg m^{-3} at Dwarka Sector 8 to 227.04 µg m^{-3} at Jahangirpuri. Jahangirpuri had the highest $PM_{2.5}$ concentration during both summer and winter, while Anand Vihar had a similar winter concentration of 225.59 µg m^{-3}.

For PM_{10}, monsoon concentrations ranged from 114.49 µg m^{-3} at R.K. Puram to 191.56 µg m^{-3} at Anand Vihar. Summer concentrations ranged from 178.88 to 246.48 µg m^{-3}, with the maximum recorded at Jahangirpuri. Winter concentrations ranged from 303.71 to 402.25 µg m^{-3}. Anand Vihar recorded the highest winter PM_{10} concentration (402.25 µg m^{-3}), whereas R.K. Puram recorded the lowest monsoon

and winter PM_{10} concentrations. Thus, the selected monitoring locations did not show identical particulate profiles: Jahangirpuri had the highest $PM_{2.5}$ seasonal means in summer and winter, while Anand Vihar had the highest winter PM_{10} mean.

The across-station $PM_{2.5}$ intervals (minimum–maximum) were 51.82–81.39 μg m^{-3} in monsoon, 69.99–86.54 μg m^{-3} in summer, and 187.81–227.04 μg m^{-3} in winter, with respective range widths of 29.57, 16.55, and 39.23 μg m^{-3}. For PM_{10}, the intervals were 114.49–191.56, 178.88–246.48, and 303.71–402.25 μg m^{-3}, with range widths of 77.07, 67.60, and 98.54 μg m^{-3}, respectively. These ranges quantify spatial differences in seasonal means; they do not measure daily extremes or within-season temporal variability.

Table 2. Station-level seasonal mean concentrations of $PM_{2.5}$ and PM_{10}

Monitoring station	$PM_{2.5}$ Monsoon	$PM_{2.5}$ Summer	$PM_{2.5}$ Winter	PM_{10} Monsoon	PM_{10} Summer	PM_{10} Winter
Anand Vihar	71.23	76.84	225.59	191.56	198.08	402.25
Dwarka Sector 8	51.82	70.06	187.81	151.91	198.75	307.07
Jahangirpuri	81.39	86.54	227.04	168.14	246.48	356.04
R.K. Puram	60.62	69.99	204.66	114.49	178.88	303.71

Note. All concentrations are expressed as μg m^{-3}.

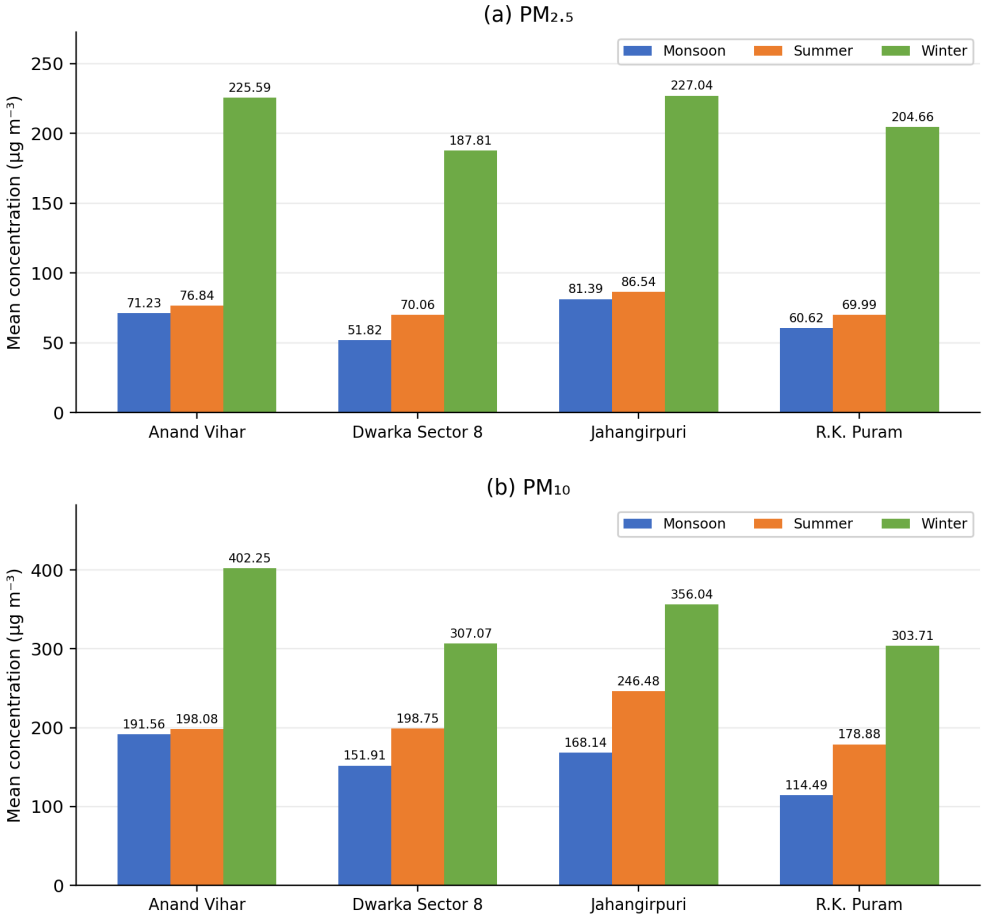


Figure 2. Station-level seasonal mean concentrations of (a) $PM_{2.5}$ and (b) PM_{10} across the four monitoring locations.

3.3. Seasonal patterns in gaseous pollutants

The gaseous pollutants showed pollutant-specific seasonal patterns (Table 1; Figures 3 and 4). The four-site mean NO concentration declined from 25.50 µg m^{-3} during monsoon to 16.94 µg m^{-3} during summer and then increased to 61.98 µg m^{-3} during winter. NO_2 increased from 34.58 µg m^{-3} during monsoon to 40.77 µg m^{-3} during summer and 73.86 µg m^{-3} during winter. The highest station-level winter NO_2 concentration was recorded at Jahangirpuri (94.10 µg m^{-3}).

The four-site mean NH_3 concentration increased from 23.86 µg m^{-3} during monsoon to 42.32 µg m^{-3} during summer and 55.58 µg m^{-3} during winter. Dwarka Sector 8 recorded the highest winter NH_3 concentration (76.59 µg m^{-3}), followed by Jahangirpuri (64.61 µg m^{-3}). SO_2 displayed a smaller seasonal range, with means of 15.30, 17.11, and 23.85 µg m^{-3} during monsoon, summer, and winter, respectively.

Ozone differed from the other pollutants. Its four-site mean increased from 26.79 µg m^{-3} during monsoon to 42.02 µg m^{-3} during summer and then decreased to 27.14 µg m^{-3} during winter. The highest summer

ozone concentration was recorded at Dwarka Sector 8 (52.89 µg m^{-3}), followed by Jahangirpuri (51.65 µg m^{-3}).

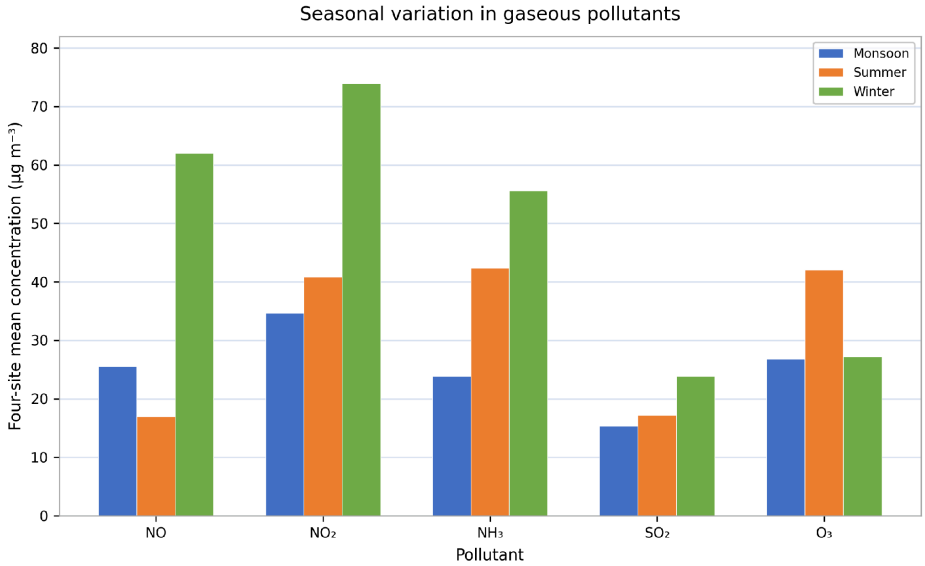


Figure 3. Four-site seasonal mean concentrations of NO, NO_2, NH_3, SO_2, and O_3.

Mean CO concentrations were 0.72, 0.68, and 1.81 mg m^{-3} during monsoon, summer, and winter, respectively. The corresponding benzene means were 1.31, 0.71, and 3.37 µg m^{-3} (Figure 4). CO and benzene are shown separately as they are reported on different concentration scales.

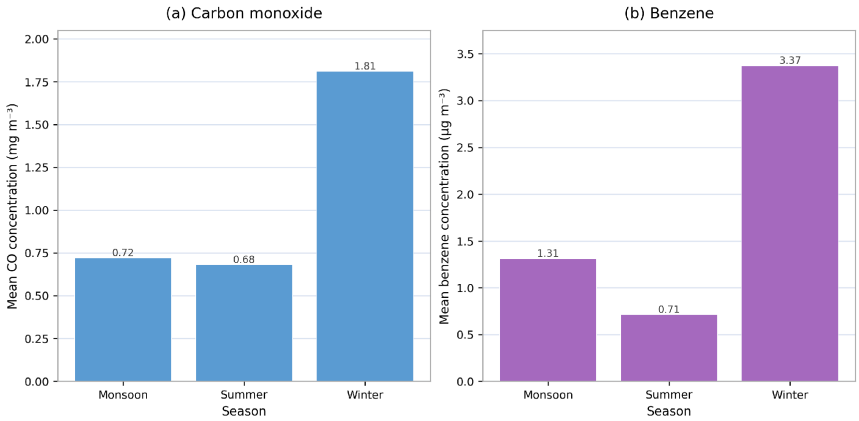


Figure 4. Four-site seasonal mean concentrations of (a) carbon monoxide and (b) benzene. Separate axes are used because CO and benzene are reported in different units.

3.4. Magnitude of winter change relative to monsoon

All nine pollutants had positive percentage change between monsoon and winter (Figure 5). $PM_{2.5}$ showed the largest increase (218.8%), followed by benzene (156.8%), CO (152.3%), NO (143.0%), NH_3

(132.9%), PM_{10} (118.7%), and NO_2 (113.6%). SO_2 increased by 55.8%. Ozone increased by only 1.3% from monsoon to winter and retained a summer maximum rather than a winter-dominated pattern.

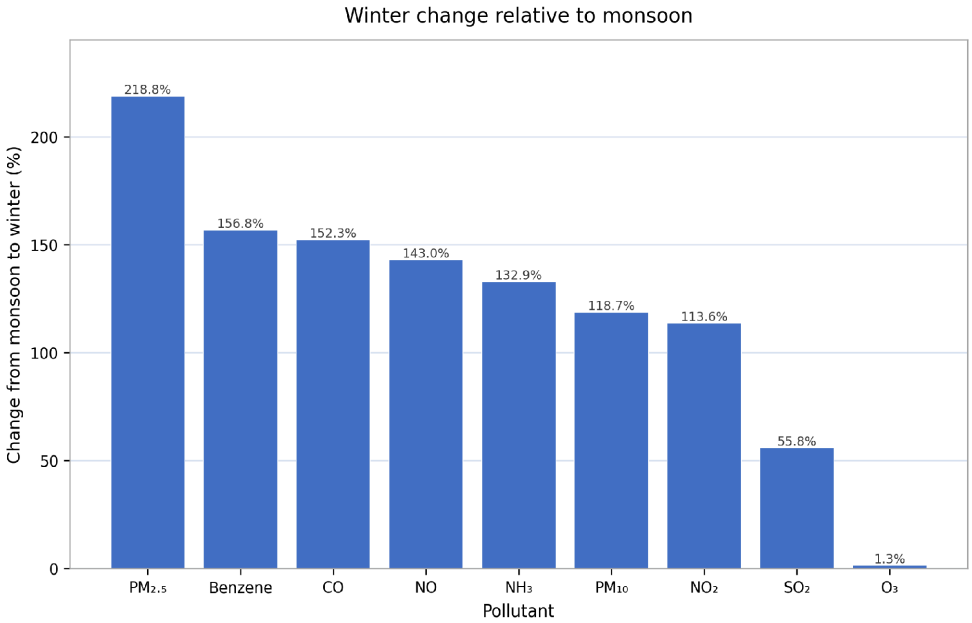


Figure 5. Percentage change in four-site mean pollutant concentrations from monsoon to winter. Positive values indicate higher winter concentrations.

4. DISCUSSION

In this study, substantial variations in ambient concentration of pollutants were observed across the different seasons and locations of Anand Vihar, Dwarka Sector 8, Jahangirpuri, and R.K. Puram. The most pronounced result was the rise in PM levels every winter at all four monitoring sites. The four-site mean $PM_{2.5}$ concentration rose from 66.27 µg m^{-3} in monsoon to 211.28 µg m^{-3} in winter, corresponding to a 218.8% increase. In this seasonal comparison, PM_{10} rose from 156.53 to 342.27 µg m^{-3}. Most gaseous pollutants also had the highest mean concentrations in winter, while ozone had a different trend and peaked in summer. The results indicate that it is not possible to present the air-quality profile of Delhi as a single pollutant or single monitoring station profile.

The greater $PM_{2.5}$ and PM_{10} increase was seen in all the monitoring stations, which showed a uniform pattern across the selected stations. In the previous studies conducted for Delhi, the particulate concentration showed similar seasonal variation, with high concentration during post-monsoon and winter season and low concentration during the monsoon season (Sharma et al., 2022; Vaishali & Das, 2025). A uniformity with the previous studies suggests that seasonal conditions play an important role in the cycle of particulate pollution in Delhi.

This winter elevation could be due to several interacting processes. Frequent temperature inversions, reduced mixing heights, and lower temperatures can limit the amount of vertical dispersion and keep

locally and regionally emitted pollutants near ground level. In Delhi, Vaishali and Das (2025) found higher $PM_{2.5}$ levels in stable boundary-layer conditions and lower mixing heights. Another study has shown that the ventilation coefficient of Delhi, the product of wind speed and the atmospheric mixing-layer height, can have a significant influence on the build-up and dissipation of air pollutants, depending on the meteorological conditions present (Saha et al., 2019).

There is also a possibility of contribution from the emission intensity. Particulate concentrations can be influenced by a combination of traffic, road-dust resuspension, waste burning, domestic fuel use, industrial emissions, construction emissions, and regional biomass burning. The source apportionment studies have indicated the role of biomass burning, residential heating, waste burning, heavy-duty vehicles, traffic, and industrial sources in the high pollution episodes observed in Delhi (Awasthi et al., 2024). The present concentration does not allow for quantification of the contribution of crop-residue burning in the neighboring Indo-Gangetic Plain, which could be especially relevant during the transition period after the monsoons.

Lower particulates during the monsoon, however, reflect increased atmospheric dispersion and rainfall removal of particulates. Fine and coarse particles can be removed from the air by wet deposition; higher winds and a deeper atmospheric boundary layer may decrease near-surface accumulation. In this study, however, October was considered to be part of the monsoon group. The inclusion of October could have caused the calculated means of monsoon to be higher than normal due to the post-monsoon transition period, characterised by low rainfall and high pollution. Further studies need to be conducted in terms of the month of October or in terms of meteorological seasons (for example: autumn, winter, spring, or summer).

Aside from the overall rise in particulate pollution in winter, the levels of pollution varied by station. Jahangirpuri had the highest $PM_{2.5}$ concentration both in summer and winter, while Anand Vihar had the highest winter PM_{10} concentration. R.K. Puram generally had the lowest level of PM_{10}, and Dwarka Sector 8 had the lowest concentration of $PM_{2.5}$ in winter. The differences suggest that the monitoring sites were sensitive to varying proportions of local emissions, land use, traffic density, urban density, and atmospheric transport.

The comparatively high concentration of PM_{10} at Anand Vihar could be attributed to the exposure to heavy traffic (including interstate traffic), resuspension of road dust, construction activity in the vicinity, and transport from surrounding areas. Coarse particles contribute more strongly to PM_{10} than to $PM_{2.5}$, which could be the reason for the prominence of Anand Vihar about PM_{10} as compared to $PM_{2.5}$. The comparatively high levels of $PM_{2.5}$ in the air at Jahangirpuri could be attributed to a different composition of $PM_{2.5}$ sources from traffic, industrial activities in the vicinity, domestic burning of waste, and high residential population density. These explanations are still hypotheses, as no chemical composition and source apportionment information were present in the CPCB concentration data which was used in this study.

The difference between the $PM_{2.5}$ and PM_{10} spatial patterns is important for air-quality management. While the location with the highest PM_{10} concentration does not necessarily have the highest $PM_{2.5}$

concentration, $PM_{2.5}$ and PM_{10} can be derived from different processes. Therefore, control measures need to be tailored to the local pollutant profile. Road dust, construction material, and mechanical resuspension are likely to be more important in locations with high coarse particle levels, while combustion sources such as vehicles, industries, waste burning, and biomass burning in the region are likely to be more important in locations with high $PM_{2.5}$.

NO and NO_2 had pronounced winter peaks. The four-site winter averages were 61.98 μg m^{-3} NO and 73.86 μg m^{-3} NO_2, while the four-site monsoon averages were 25.50 μg m^{-3} NO and 34.58 μg m^{-3} NO_2. NOx is a byproduct of combustion from road transport, power generation, industrial sources, and urban activities. They are therefore in agreement with a decrease in the dispersion in the atmosphere during winter. However, it is not possible to assess the relative contribution from each emission source from the present analysis.

The winter enhancement was also very strong for CO and benzene. The levels of CO and benzene were 152.3% and 156.8%, respectively, higher during winter than their corresponding mean during the monsoon season. Pollutants can both be linked to incomplete combustion and to emissions from traffic, but benzene can also come from fuel evaporation, industry, use of solvents, and biomass burning. Previous studies have also linked elevated concentrations of benzene in the winter season in the Delhi-NCR region with reductions in planetary boundary-layer heights (Kaushik et al., 2024). The high levels of CO, benzene, NO, NO_2, and particulate matter during the winter are consistent with the effects of winter combustion emissions and unfavourable dispersion conditions. The concentration patterns, however, do not prove that these pollutants were derived from a common source.

The NH_3 concentration rose from 23.86 μg m^{-3} at four sites to 55.58 μg m^{-3} in winter. Sources of ammonia can include waste handling, sewage, agriculture, traffic, and other urban/regional sources. It is also involved in the generation of secondary inorganic aerosols (SIAs) by reacting with acidic atmospheric compounds. The NH_3 levels found high in the winter season at Dwarka Sector 8 and Jahangirpuri could thus be of relevance to fine-particle formation. Analysis with meteorological and aerosol-composition datasets would be needed to assess the direct contribution of elevated NH_3 to the observed $PM_{2.5}$ concentrations.

The seasonal trend of SO_2 was less pronounced than for the other winter-dominated pollutants. Its winter mean was 55.8% higher than its monsoon mean, while the increases were over 100% for $PM_{2.5}$, PM_{10}, NO, NO_2, NH_3, CO and benzene. This reduced relative variation could reflect variations in the spatial distribution, seasonal intensity, or control of sulphur emission sources. It could also be due to conversion of SO_2 to sulphate aerosols in the atmosphere. The possibility was not assessed because the sulphate concentrations were not available in the dataset.

The main exception to the winter dominant pattern of pollution was ozone. During the monsoon, its four-site mean was 26.79 μg m^{-3}, while in summer, it was 42.02 μg m^{-3} and in winter, 27.14 μg m^{-3}. Ground-level ozone is a secondary pollutant created through photochemical reactions between VOCs and nitrogen oxides. The summer maximum can be explained by the increase in both temperature and sun radiation intensity in summer, which can strengthen these reactions.

The relationship between ozone and NOx is complicated. NO of high concentration can lead to local reductions in the amount of ozone formation, while NO_2 and VOCs can increase the amount of ozone formation when sunlight is present. Hence, this lower winter mean of O3 should not be seen as a general improvement in air quality during winter. Rather, it indicates a different atmospheric-chemistry scenario in which primary pollutants accumulate more readily, with the ozone production by the photochemical reactions being relatively small. Spatial and temporal variability between surface ozone and nitrogen oxides (NOx) have been shown from previous studies across Delhi-NCR region (Kumar et al., 2015).

These elevated summer ozone concentrations at Dwarka Sector 8 and Jahangirpuri indicate that ozone-control measures should not be limited to areas of highest particulate concentrations. The station with the high ozone concentration does not necessarily represent the site of the release of the precursor pollutants because ozone can form downwind of the sources of its precursors. So, coordinated management of Nox and VOC in the broader Delhi-NCR air shed would be necessary for effective management.

The results validate a pollutant- and location-specific approach in air-quality management. The strong winter is seen in several pollutants, which suggests that emergency measures during the winter should be undertaken based on the season and not specifically when winter stagnation becomes significant. Regional coordination of transported pollution as well as tighter control of transport pollution, road and construction dust, open waste burning, industrial combustion and other local sources of pollution may be considered.

The unique spatial profiles also suggest that there may be differing outcomes of interventions in different monitoring areas. Anand Vihar might need special focus on combustion sources, including road dust and traffic as well as nearby and regional combustion sources at Jahangirpuri, where the $PM_{2.5}$ levels are high. Meanwhile, the summer ozone peak highlights the need for year-round precursor pollution control, not just particulate-matter pollution control in the winter.

These results need to be interpreted with a few caveats. The analysis covered only four monitoring stations and hence does not capture all the residential, commercial, industrial, roadside, and background environment in Delhi. Finally, the study was conducted over 1 year of a seasonal cycle and cannot detect long-term trends unless they are caused by meteorological or emission conditions for the year. Third, the four-site seasonal results were computed as unweighted means, with the number of valid observations varying somewhat by pollutant, station, and season. In some station-season combinations, missing observations were particularly relevant with regard to benzene and ozone.

Fourth, the analysis was descriptive. Spatial ranges were calculated for particulate-matter seasonal means, but daily variability measures, confidence intervals, and formal statistical tests were not available. Seasonal means can therefore conceal extreme episodes and differences in day-to-day variability. The observed differences should not be interpreted as statistically significant without an appropriate inferential analysis. Fifth, wind speed, wind direction, rainfall, temperature, relative humidity, boundary-layer height, traffic activity, fire counts, and pollutant-source profiles were not included in the dataset. The proposed

meteorological and emission-related explanations, therefore, have to be confirmed by other analysis, but cannot be confirmed by the present analysis.

Even with these restrictions, the study offers a clear comparison between different pollutants in four different and contrasting monitoring sites. A multi-pollutant, multi-location, and differentiated seasonal assessment of the air quality condition in Delhi clearly highlights the consistency of the winter increase in particulate matter, as well as some spatial variations in pollutant concentrations and the maximum in summer ozone.

5. CONCLUSION

This study demonstrates clear seasonal and spatial variation in air-pollutant concentrations. The present study shows that the concentration of air pollutants at Anand Vihar, Dwarka Sector 8, Jahangirpuri and R.K. Puram has substantial seasonal and spatial variations. The highest mean concentrations were observed during the winter, with $PM_{2.5}$ and PM_{10} concentrations rising by 218.8% and 118.7%, respectively, over the monsoon. The highest concentration of $PM_{2.5}$ was recorded by Jahangirpuri in both summer and winter, while the highest concentration of PM_{10} was recorded by Anand Vihar in winter. Ozone was highest in the summer season instead, and had a different pattern than the primary pollutants. The results provide support for seasonal and location-specific air-quality management, and the interventions for winter should be targeted at particulate and combustion-related emissions, while those for summer should be targeted at emissions of ozone precursors.

The present study focuses on four monitoring stations for one annual monitoring cycle, and further analyses involving inferential statistics, meteorological variables, and source apportionment data would allow a more thorough interpretation of patterns observed. The analysis can be extended to more stations and years to further establish the temporal consistency and spatial representativeness of the findings and reinforce the use of these results for evidence-based air-quality management in Delhi.

REFERENCES

1. Awasthi, A., Sinha, B., Hakkim, H., Mishra, S., Mummidivarapu, V., Singh, G., Ghude, S. D., Soni, V. K., Nigam, N., Sinha, V., & Rajeevan, M. N. (2024). Biomass-burning sources control ambient particulate matter, but traffic and industrial sources control volatile organic compound (VOC) emissions and secondary-pollutant formation during extreme pollution events in Delhi. *Atmospheric Chemistry and Physics, 24*, 10279–10304. https://doi.org/10.5194/acp-24-10279-2024

2. Commission for Air Quality Management. (2024, December 31). *2024—Air quality perspective in Delhi*. Ministry of Environment, Forest and Climate Change, Government of India. https://www.pib.gov.in/PressReleasePage.aspx?PRID=2089055

3. Garsa, K., Khan, A. A., Jindal, P., Middey, A., Luqman, N., Mohanty, H., & Tiwari, S. (2023). Assessment of meteorological parameters on air pollution variability over Delhi. *Environmental Monitoring and Assessment, 195*, Article 1315. https://doi.org/10.1007/s10661-023-11922-2

4. Hama, S. M. L., Kumar, P., Harrison, R. M., Bloss, W. J., Khare, M., Mishra, S., Namdeo, A., Sokhi, R., Goodman, P., & Sharma, C. (2020). Four-year assessment of ambient particulate matter and trace gases in the Delhi-NCR region of India. *Sustainable Cities and Society, 54*, Article 102003. https://doi.org/10.1016/j.scs.2019.102003

5. Kaushik, N., Mishra, A. K., & Das, R. M. (2024). Assessment of benzene and toluene emissions in National Capital Region (NCR): Implications for health risks and ozone formation. *Air Quality, Atmosphere & Health, 17*, 3015–3029. https://doi.org/10.1007/s11869-024-01618-y

6. Kumar, A., Singh, D., Singh, B. P., Singh, M., Anandam, K., Kumar, K., & Jain, V. K. (2015). Spatial and temporal variability of surface ozone and nitrogen oxides in urban and rural ambient air of Delhi-NCR, India. *Air Quality, Atmosphere & Health, 8*, 391–399. https://doi.org/10.1007/s11869-014-0309-0

7. Kumar, P., Garg, A., Sharma, K., Nadeem, U., Sarma, K., Gupta, N. C., Kumar, A., & Pandey, A. K. (2024). Seasonal and spatial variations in particulate matter, black carbon and metals in Delhi, India's megacity. *Urban Science, 8*(3), Article 101. https://doi.org/10.3390/urbansci8030101

8. Saha, D., Soni, K., Mohanan, M. N., & Singh, M. (2019). Long-term trend of ventilation coefficient over Delhi and its potential impacts on air quality. *Remote Sensing Applications: Society and Environment, 15*, Article 100234. https://doi.org/10.1016/j.rsase.2019.05.003

9. Shankar, S., & Gadi, R. (2022). Variation in air quality over Delhi region: A comparative study for 2019 and 2020. *Aerosol Science and Engineering, 6*, 278–295. https://doi.org/10.1007/s41810-022-00144-7

10. Sharma, P., Peshin, S. K., Soni, V. K., Singh, S., Beig, G., & Ghosh, C. (2022). Seasonal dynamics of particulate matter pollution and its dispersion in the city of Delhi, India. *Meteorology and Atmospheric Physics, 134*, Article 28. https://doi.org/10.1007/s00703-021-00852-8

11. Vaishali, & Das, R. M. (2025). Seasonal and diurnal variability of $PM_{2.5}$ concentration along with the role of wind patterns over different locations of Delhi during the year 2018 to 2022. *Environmental Monitoring and Assessment, 197*, Article 350. https://doi.org/10.1007/s10661-025-13761-9

12. World Health Organization. (2021). *WHO global air quality guidelines: Particulate matter ($PM_{2.5}$ and PM_{10}), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide*. https://www.who.int/publications/i/item/9789240034228