



Spatial and Temporal Assessment of Air Pollution and Meteorological Influences Across Major Indian Cities

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Abstract

Air pollution is a key environmental issue in fast growing urban cities of India, with high spatial, seasonal and meteorological fluctuations in pollutant levels. In this study, air pollution spatial and temporal patterns were evaluated and the impact of meteorological variables on air pollution across 29 major cities in India was explored based on 1450 balanced observations taken from 2022-2025. Major pollutants like $PM_{2.5}$, PM_{10} , CO, NO_2 , SO_2 , O_3 , Air Quality Index (AQI) and meteorological parameters like Humidity, Dew point, Wind gust, Precipitation, Air pressure and cloud cover were analyzed. Descriptive statistics, city-wise and seasonal comparisons, Pearson correlation analysis and multivariable linear regression was used. Spatial variation was evident with the northern and more urbanized cities generally having higher pollution burdens while several northeastern, coastal and hill cities had lower pollution burdens. The air quality in the winter season and post monsoon was comparatively poor, while the particulate pollution and AQI were lower during monsoon. Meteorological parameters showed significant association with pollution variability, in general humidity, wind gusts and cloud cover were negatively associated while atmospheric pressure was positively associated with $PM_{2.5}$, PM_{10} and AQI. The results indicate the need to consider spatial, seasonal, and meteorological data in urban air-quality management. City-specific and season-specific mitigation strategies could help better control pollution and environmental planning for sustainability in India.

Keywords:

- Air pollution
- Meteorological factors
- Spatial variation
- Temporal variation
- Indian cities

1. Introduction

Air pollution is one of the most persistent environmental problems caused by the rapid urbanization and industrialization, growth in energy consumption, and changing land-use patterns. Particulate and gaseous pollutants, like particulate matter ($PM_{2.5}$ and PM_{10}), nitrogen dioxide (NO_2), sulphur dioxide (SO_2), carbon monoxide (CO) and ozone (O_3) continuously affect urban population. Air pollution is a key issue for sustainable urban development, as these pollutants have impacts on atmospheric quality, ecosystem functioning, climatic processes and human well-being. Rapid growth of metropolitan regions has compounded the pollution-related pressures in India, and climatic variability and changing meteorology affects pollutants' behaviour and exposure patterns (Kaur & Pandey, 2021). Based on the large-scale observation, significant spatial and temporal variations in atmospheric pollution over India has also been identified, which highlights the need for regional and multi-city assessments (Kuttiappurath et al., 2020).

The concentration of air pollutants is different across the cities of India, depending on population density, traffic volumes, industrial and fuel consumption, the construction process, geographic location and other emission sources. Multi-city evaluation shows that there is not a uniform pattern of atmospheric pollution across the Indian urban regions and that it may react differently to changes in anthropogenic activities (Vadrevu et al., 2020). The same geographical variations have been found at different locations under different environmental conditions, indicating the strong modifications of pollutant concentrations by local climate and regional characteristics (Varaprasad et al., 2021). The studies are also Delhi-centric with its nearby areas and have pointed out the complex temporal and spatial variation of pollution, especially for particulate matter and gaseous contaminants (Kumar et al., 2022). Similarly, temporal variation between major metros like Delhi and Bengaluru also shows the need to assess air quality over various time periods and not just annual averages (Meda & Mathew, 2022).

Seasonal and temporal variations are of special interest, as they affect the accumulation, transport, transformation and removal of pollutants. The urban thermal conditions can change the stability of the atmosphere and the distribution of pollutants in the atmosphere, creating some interaction between UHI and AP (Mishra & Mathew, 2022). In the local scale, the urban heat-island effects can alter the local meteorological parameters such as temperature, wind, etc., and consequently the air-quality parameters in urban microenvironments (Swamy et al., 2020). Meteorological variables like relative humidity, precipitation, atmospheric pressure, dew point, cloud cover and wind dynamics can accordingly be significant contributors to pollutant concentration variations. The statistical analysis has shown significant relations between meteorological parameters and air pollutants in fast-growing Indian urban areas (Bose & Roy Chowdhury, 2023). The influence of meteorological variability on the change in pollution levels in Delhi has also been identified (Garsa et al., 2023).

There is a growing focus on integrated spatiotemporal assessment for improved understanding of the dynamics of air-pollution. The geospatial investigations have demonstrated that the pollutant concentration in cities can vary significantly in space and time, depending on the environmental and anthropogenic conditions (Gond et al., 2024). Additionally, studies in northern Indian cities have reported correlations between the temporal variation of pollutants and meteorological parameters, further emphasizing the importance of accounting for both temporal and meteorological aspects of air pollutants together (Soni et al., 2024). The seasonal and annual evaluation in Bengaluru also reveals that particulate and gaseous pollutants have different temporal trends, which can differ based on local

atmospheric conditions (Suthar et al., 2024). In a broader context, recent observations in Indian megacities suggest a strong relationship between urban air-pollution trends and climatic/environmental factors, and the need for multi-city comparative studies (Gulia et al., 2025). In this context, despite the availability of this literature, integrated analyses which consider spatial differences, temporal variability, and meteorological influences simultaneously for a wide range of major cities in India are useful for better monitoring of the environment and for assisting in air quality management in these cities.

Objectives:

- To assess the spatial variation of major air pollutants and AQI across selected major Indian cities.
- To examine the temporal and seasonal patterns of air pollution during the study period.
- To evaluate the relationships between meteorological conditions and major air-pollution indicators across the selected cities.

2. Materials and Methods

2.1 Study Design

The study used quantitative observational approach to assess the spatial and temporal distribution of air pollution and the correlation between air pollution and meteorological parameters in the major cities of India. Secondary data on the environment was analysed to determine the level of pollution concentrations in different cities and between temporal categories (month, season, day and time). The study also investigated statistical associations among meteorological parameters and large air-quality indicators to see if there were any relationships between the atmospheric conditions and changes in urban air quality.

2.2 Data Source and Study Dataset

A multi-city air-quality and meteorological dataset was cleaned to a total of 1,450 observations (Vekariya, 2025). Observations were obtained for 29 major cities, and 50 observations were kept for each city to ensure a proper spatial representation. The data included in each record were geographical, temporal, meteorological, and air-pollution data. The study period (2022–2025) was conducive to assessing air quality fluctuations in urban areas over various time scales. Only those variables that were directly related to the objectives of the study were used in the final analysis.

2.3 Study Area and Spatial Variables

The study comprised of important cities in various states and geographical areas of India. City name and state, and latitude and longitude were used to represent spatial information. The participation of cities in various geographical conditions allowed to assess the differences in air-pollution levels among cities. Geographical distribution of the study locations was characterized using latitude/longitude coordinates, and this was used for spatial interpretation of pollutant patterns.

2.4 Air-Pollution Variables

The assessment of air-quality was carried out with major particulate and gaseous pollutants available in the dataset. The concentration of $PM_{2.5}$ and PM_{10} were used to represent particulate pollution and CO , NO_2 , SO_2 and O_3 concentrations were used for gaseous pollution. Other environmental pollution indicators were dust concentrations and AOD. The United States Air Quality Index (AQI) and the AQI category were used to represent the overall air-quality conditions. Overall pollution levels and air quality comparison between cities and time periods was done with these variables.

2.5 Meteorological Variables

Meteorological conditions were determined by the following parameters—relative humidity, dew-point temperature, wind-gust speed, precipitation, mean sea-level atmospheric pressure, and cloud-cover percentage. These parameters were chosen for they can influence the dispersion, accumulation, transport, chemical transformation and removal of pollutants from the atmosphere. They assessed their relationships with the particulate and gaseous pollutants and established if there were changes in the air-quality indicators that were correlated with changes in meteorological conditions.

2.6 Temporal Classification

Temporal variation was evaluated based on the date and time recorded and by month, day of the week, season and time of day. The periods of summer, monsoon, post-monsoon and winter were considered as the seasonal categories.

These classes allowed the analysis of the pollutant concentrations changes under various season and time conditions. The multi-year coverage also enabled to compare the general trends of changes in pollution levels during the study period.

2.7 Data Cleaning and Preparation

A screening of the data set was done prior to statistical analysis to ensure consistency and completeness. Data was deduplicated and checked for missing or invalid data. To ensure a balanced sampling approach, the same number of observations was taken in each of the 29 cities. Variable names and measurement units were standardized, and numerical variables were assessed for appropriate data types and reasonable ranges. The final number of observations was 1,450 and the number of variables was 25 concerning the spatial and temporal aspects of the study, the meteorological conditions, and the air-quality measurements.

2.8 Statistical Analysis

Air-pollution and meteorological variables were summarized by descriptive statistics (mean, standard deviation, median, minimum and maximum). Spatial and temporal variations were assessed through the comparison of data for each year and season, and between cities. Pearson correlation was applied to evaluate the relationships among meteorological parameters and major pollutants. Multivariable linear regression was used to look at the effects of the meteorological parameters on PM_{2.5}, PM₁₀, and AQI. The statistical significance was $p < 0.05$ and analysis was carried out using Python in Google Colab.

2.9 Ethical Considerations

The study did not involve human or animal subjects, or personal identifiers or confidential information. Hence, formal ethical approval and informed consent were not necessary. Only academic research activities were conducted using the dataset, and data handling and analysis were done in line with the values of research integrity and transparent reporting.

3. Results

3.1 Overall Air-Pollution and Meteorological Characteristics

Descriptive analysis showed considerable variation in particulate matter, gaseous pollutants, AQI, and meteorological conditions over the course of the study observations. There was a wide range in particulate concentrations, indicating a high degree of variability in the air-quality state of the different urban environments selected. The same behaviour was observed for the gaseous pollutants: CO, NO₂, SO₂ and O₃. For the meteorological parameters, significant differences were also found between the measurements so that a suitable basis for examining the relationships with the pollution parameters exists. Overall descriptive characteristics are given in Table 1.

Table 1. Descriptive statistics of air-pollution and meteorological variables

Variable	Mean	SD	Median	Minimum	Maximum
PM _{2.5} (µg/m ³)	33.44	26.55	26.10	1.90	183.50
PM ₁₀ (µg/m ³)	49.55	45.51	38.05	2.30	420.00
CO (µg/m ³)	431.80	331.57	335.00	96.00	2903.00
NO ₂ (µg/m ³)	15.69	19.58	9.00	0.00	122.10
SO ₂ (µg/m ³)	13.61	18.08	7.10	0.20	134.20
O ₃ (µg/m ³)	89.27	46.06	82.00	0.00	228.00
US AQI	97.09	46.81	86.00	19.00	289.00
Humidity (%)	67.33	21.10	71.00	10.00	100.00
Dew point (°C)	16.59	6.95	17.45	-6.10	27.30
Wind gusts (km/h)	19.93	9.41	18.40	3.20	55.10

Precipitation (mm)	0.15	0.67	0.00	0.00	7.70
Pressure (hPa)	1010.01	5.16	1010.20	993.90	1022.80
Cloud cover (%)	45.21	43.15	28.00	0.00	100.00

3.2 Spatial Variation in Air Pollution Across Cities

Spatial heterogeneity was found among the 29 cities. Northern cities and those with high urbanization generally featured in the top half of the city-wise average AQI, while a few northeastern, coastal and hill cities exhibited comparatively lower average pollution. Gurugram and Delhi presented the highest overall pollution burden in the balanced city sample, while Itanagar, Kohima, Aizawl and Thiruvananthapuram were some of the cities with relatively low AQI. The detailed city-wise comparison is given in Table 2 and the spatial contrast in mean AQI is given in Figure 1.

Table 2. City-wise mean concentrations of selected pollutants and AQI

City	PM _{2.5}	PM ₁₀	NO ₂	O ₃	US AQI
Gurugram	70.80	138.15	46.54	93.40	164.64
Delhi	63.46	112.46	38.76	96.44	152.22
Patna	55.69	76.58	16.45	103.26	138.58
Lucknow	52.63	77.34	15.72	101.64	132.12
Raipur	47.87	64.36	29.78	84.90	129.64
Kolkata	50.01	66.01	20.91	97.82	121.76
Mumbai	42.36	64.55	25.28	106.04	116.98
Chandigarh	38.39	53.79	21.55	97.88	115.14
Jaipur	36.22	69.26	17.45	96.68	110.58
Agartala	37.63	49.33	24.54	81.18	110.48
Ranchi	34.47	48.69	9.41	101.10	106.26
Bhubaneswar	37.69	51.00	10.61	95.60	105.18
Visakhapatnam	37.74	52.82	32.22	77.96	103.82
Dehradun	28.17	38.85	15.21	94.36	91.78
Ahmedabad	29.54	47.84	18.77	78.54	90.82
Bhopal	30.26	44.17	5.73	92.74	89.62
Hyderabad	26.32	35.93	12.65	91.26	88.90
Guwahati	29.35	38.85	6.60	86.20	88.84
Chennai	24.08	36.36	11.07	84.78	77.36
Imphal	21.49	27.81	10.31	76.46	74.54
Panaji	22.47	32.21	6.64	74.36	74.38
Bengaluru	21.97	29.88	17.47	76.80	73.04
Shimla	20.05	29.39	11.49	90.46	71.68
Gangtok	20.97	27.48	6.40	96.84	70.84

Shillong	19.11	25.59	5.11	88.46	68.00
Thiruvananthapuram	17.77	27.72	2.66	93.18	65.34
Aizawl	17.73	23.63	5.93	70.76	62.08
Kohima	18.03	23.55	6.20	78.00	61.94
Itanagar	17.48	23.27	3.54	81.62	58.98

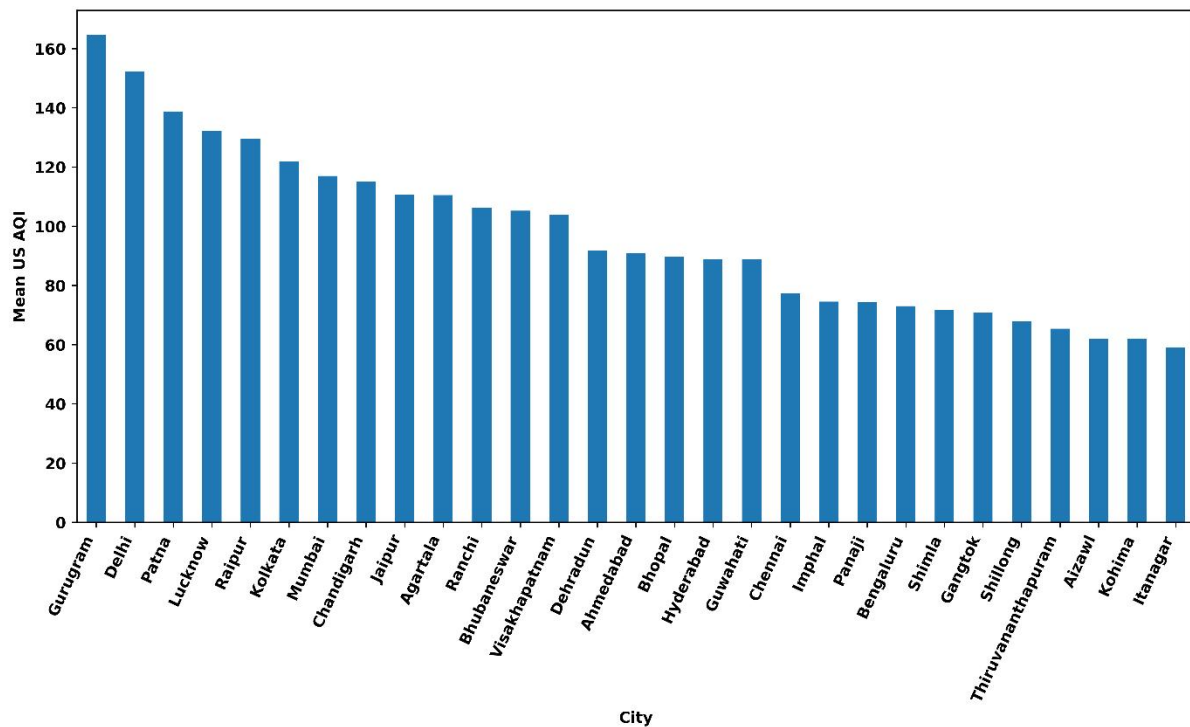


Figure 1. Mean Air Quality Index across major Indian cities

As shown in Figure 1, the city ranking demonstrated clear spatial heterogeneity, with Gurugram and Delhi showing the greatest mean AQI burden and several northeastern cities occupying the lower end of the distribution.

3.3 Temporal Variation in Air-Pollution Indicators

The annual analysis showed varying rather than a consistent linear pattern over the years of the study. Particulate pollution was relatively high at the start of the study period but decreased after that and remained relatively steady for the following years. NO_2 exhibited a more evident decrease beyond 2022, while O_3 showed an overall trend of higher levels in the later years. The AQI fluctuated between each year and was relatively high during the last study year. The annual variations are summarised on Table 3.

Table 3. Year-wise variation in major air-quality indicators

Year	PM _{2.5}	PM ₁₀	NO ₂	O ₃	US AQI
2022	37.11	55.04	23.42	77.98	98.64
2023	30.94	48.23	17.26	90.43	94.59
2024	33.67	50.77	12.30	90.67	93.69
2025	33.85	46.80	13.89	92.24	102.45

3.4 Seasonal Variation in Air Quality

There was a clear pollution trend associated with the four climatic periods. Overall, the AQI and particulate load was highest in winter, with post-monsoon and summer conditions following. However, the lowest particulate concentrations and AQI were observed during monsoon conditions, suggesting more favourable atmospheric conditions for removal and dispersion of pollutants. The seasonal variation of O₃ was found to be a bit different with higher concentration in post-monsoon. Table 4 shows the seasonal mean values, and the overall contrast is shown in Figure 2.

Table 4. Seasonal variation in major air-quality indicators

Season	PM _{2.5}	PM ₁₀	NO ₂	O ₃	US AQI
Winter	44.45	62.08	18.26	91.50	113.70
Summer	33.15	54.92	16.75	88.32	102.19
Monsoon	18.57	30.20	9.67	78.80	68.06
Post-monsoon	38.41	52.36	18.36	98.54	106.07

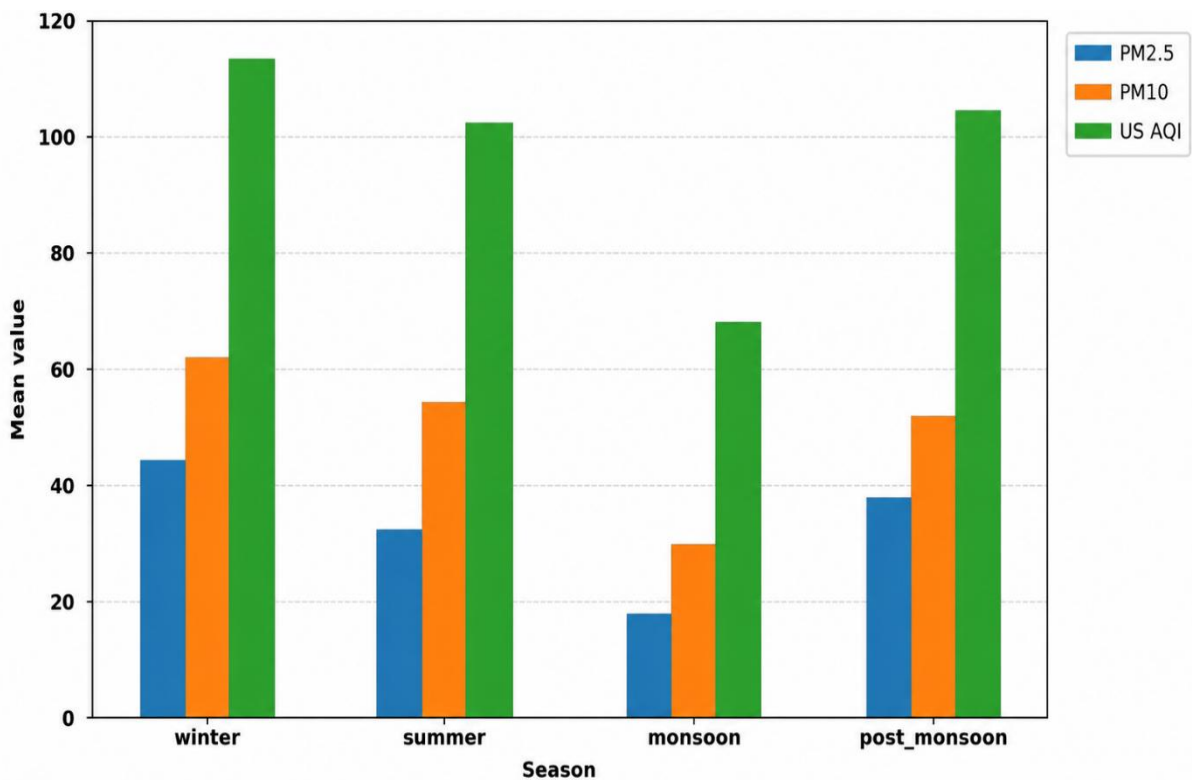


Figure 2. Seasonal variation in PM_{2.5}, PM₁₀, and AQI

As illustrated in Figure 2, seasonal differences were most evident between winter and monsoon conditions, confirming a pronounced temporal component in urban air-quality variability.

3.5 Distribution of AQI Categories

The categorical assessment indicated that the most common category was moderate air quality. A large proportion of observations, however, were in categories that could be interpreted as a potential health concern, such as unhealthy

for sensitive Groups and unhealthy conditions. Bad air quality was relatively rare and good air quality made up a smaller proportion of the overall data. This summary of the categorical distribution is shown in Table 5 and in Figure 3.

Table 5. Distribution of AQI categories

AQI Category	Frequency	Percentage (%)
Good	217	15.0
Moderate	658	45.4
Unhealthy for Sensitive Groups	289	19.9
Unhealthy	268	18.5
Very Unhealthy	18	1.2
Total	1450	100.0

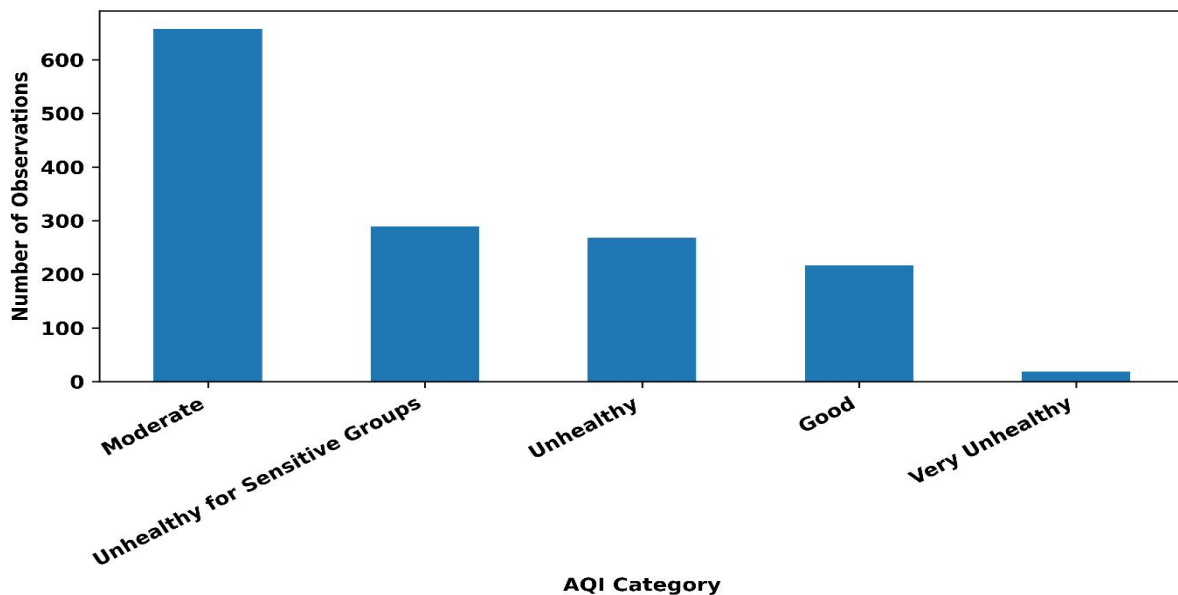


Figure 3. Distribution of AQI categories across the study observations

The pattern in Figure 3 demonstrates that most observations were concentrated in the moderate and health-relevant AQI categories rather than consistently good air-quality conditions.

3.6 Relationships Between Meteorological Conditions and Air Pollution

The Pearson correlation analysis showed a predominant negative correlation between humidity related, wind related, precipitation related and cloud cover variables and $PM_{2.5}$, PM_{10} and AQI. Positive correlation with the three indicators was found with atmospheric pressure. Overall, the relationships were weak to moderate in magnitude but best correlated with $PM_{2.5}$ and pressure, humidity and AQI, and cloud cover and AQI. The full correlation results are displayed in Table 6 and Figure 4 illustrates the direction and strength of the correlations.

Table 6. Pearson correlations between meteorological variables and air-quality indicators

Meteorological Variable	$PM_{2.5}$	PM_{10}	US AQI
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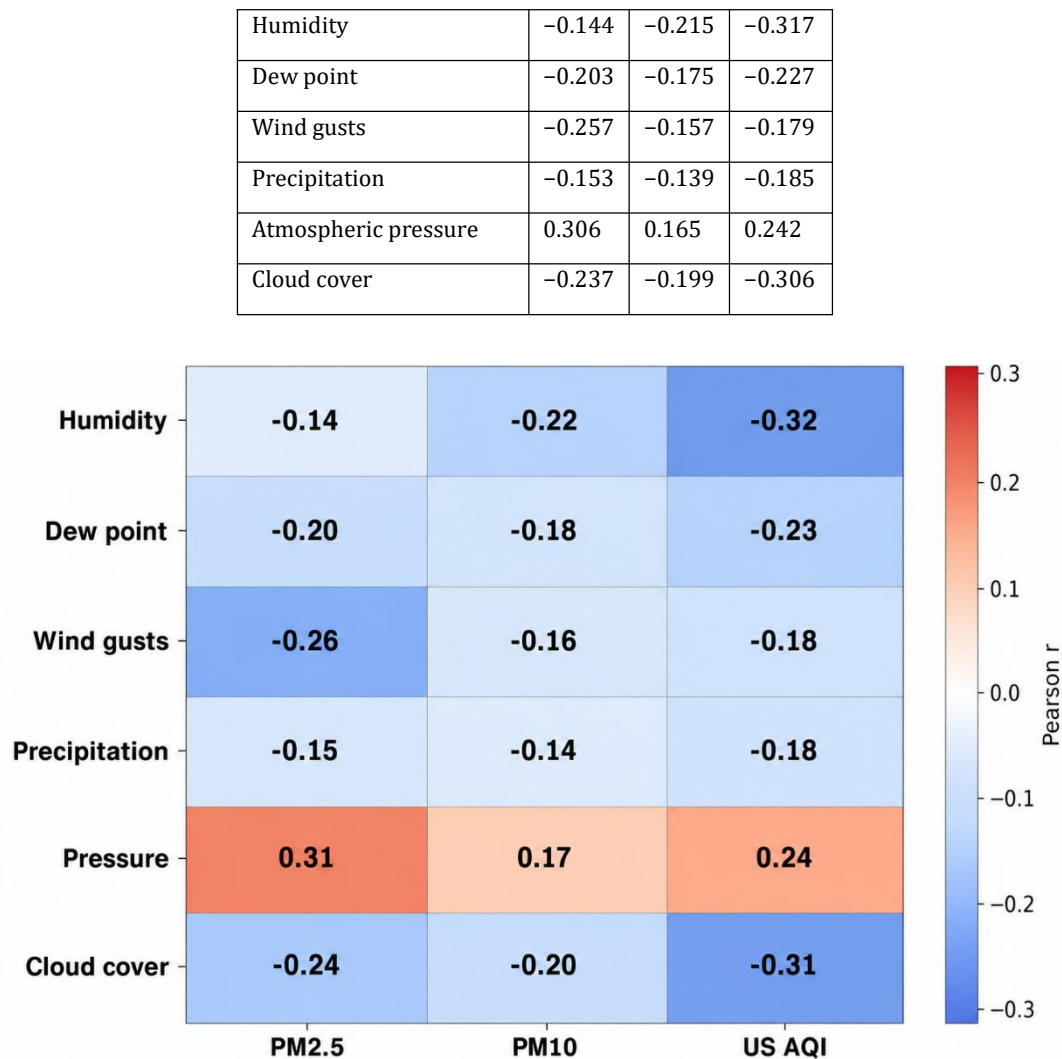


Figure 4. Correlation heatmap of meteorological variables with PM_{2.5}, PM₁₀, and AQI

The heatmap in Figure 4 highlights the contrasting behaviour of atmospheric pressure relative to the predominantly negative associations observed for the remaining meteorological parameters.

3.7 Multivariable Influence of Meteorological Factors

Previous investigation of the effects of meteorological factors on PM and AQI revealed that a significant fraction of variability in both was contributed by meteorological factors as a group in a multivariable regression analysis. The explanatory power of AQI was highest followed by PM_{2.5} and PM₁₀. Humidity and wind gusts were always correlated to the reduction of pollution outcomes, and atmospheric pressure was positively correlated in all three models. After simultaneously controlling for the other meteorological variables, dew point was positively associated. Precipitation failed to show any statistically significant independent association in any model, but cloud cover was significant for PM_{2.5} and AQI but not PM₁₀. The results of the detailed regression are presented in Table 7.

Table 7. Multivariable linear regression of meteorological influences on PM_{2.5}, PM₁₀, and AQI

Predictor	PM _{2.5} B (p)	PM ₁₀ B (p)	AQI B (p)
Humidity	-0.265 (<0.001)	-0.579 (<0.001)	-0.902 (<0.001)
Dew point	0.664 (<0.001)	0.735 (0.007)	1.602 (<0.001)
Wind gusts	-0.630 (<0.001)	-0.858 (<0.001)	-1.012 (<0.001)

Precipitation	-1.371 (0.178)	-2.596 (0.152)	-2.272 (0.193)
Atmospheric pressure	1.528 (<0.001)	1.185 (<0.001)	2.255 (<0.001)
Cloud cover	-0.050 (0.004)	-0.052 (0.100)	-0.124 (<0.001)
Model R ²	0.168	0.103	0.212

In general, the results show a spatial and temporal heterogeneity of the urban air pollution, and measurable correlations between meteorological parameters and air-quality indicators. The results obtained from Tables 1–7 and Figures 1–4 directly address the study objectives related to the spatial variation, temporal trend and meteorological influence on the major cities of India.

4. Discussion

The current study revealed that there is a definite spatial, temporal and meteorological variation in urban air pollution in major cities of India. City-wise analysis revealed that northern and more metropolitan cities were more polluted as compared to some other cities in the northeast, coastal and hill regions with comparatively low AQI. Seasonal analysis also revealed that the particulate pollution and AQI were generally higher in the winter and post-monsoon seasons as compared to the monsoon season, which had the lowest particulate pollution level. These findings indicate that the air quality in Indian cities depends on the emission intensity, geographic characteristics of the region, atmospheric conditions and meteorological phenomenon during the different seasons. Delhi, with its shared seasonal pollution pattern, has been reported to have significant modulation in pollution levels due to meteorology and/or source variability (Ansari et al., 2025). Similarly, the spatiotemporal variations over Uttar Pradesh (eastern part) are also correlated with pollutant variations in space and time (Bhatla et al., 2025).

The spatial variations as identified by this study agree with recent regional studies, which have shown that air pollution is not homogeneously spread across northern India. Pollutant concentrations were found to be significantly different across the region and based on the weather system, which again highlighted the need for multi-city comparisons (Kumar et al., 2025) in western Uttar Pradesh. This inter-city heterogeneity observed may be due to the differences in traffic, industrial activity, construction, population density, land use and atmospheric dispersion. Temporal aspects also play a role, since urban pollution may fluctuate between hours or day and night. Pollutants concentration has been observed to have significant differences between day and night conditions, especially with variations in heat and atmosphere across Indian megacities (Mehta et al., 2025). Similarly, the seasonal variations in the sources and surface meteorology have been demonstrated to affect the pollutant build-up and dispersion in Delhi (Prakriti et al., 2025).

Meteorological analysis results showed that most of the meteorological factors including humidity, dew point, wind gusts, precipitation and cloud cover were negatively associated with particulate pollution and AQI, whereas atmospheric pressure was positively associated. This indicates that the wet deposition, ventilation and moisture might decrease pollutant concentration and more stable high pressure might promote accumulation. Similar multivariate analysis has revealed that pollution dynamics are significantly related to thermal and atmospheric environment (Rahaman et al., 2025). The pollution pattern seasonal and diurnal observations received in Faridabad further confirms the role of meteorology in controlling the pollutants variability (Ravish & Kashyap, 2025). Further analysis of the long-term observations made at the coastal stations of India also shows a significant impact of synoptic meteorology on air-quality behaviour over time (Resmi et al., 2020).

The pollutant-specific results are also in alignment with the recent study which investigated the association between particulate matter, gaseous pollutants and urban thermal conditions (Sharma et al., 2025). The particulate accumulation during wintertime observed in the present study aligns with the previous findings from Delhi, where the lower dispersion of particulates in the atmosphere and their seasonal stagnation increased the concentration of particulates (Sharma et al., 2022). Such seasonal pollutant–meteorology relationships have been reported elsewhere in the urban environment, suggesting the general environmental significance of such interactions (Shelton et al., 2022). Highly resolved observations of PM_{2.5} in the Indo-Gangetic Plain have also shown the fossil fuel combustion to be heavily weather dependent for the pollution episodes (Shukla et al., 2025). The spatial and seasonal trends observed here have been corroborated by nationwide analysis of NO₂ that has also shown evidence of distinct spatial and temporal variations over India (Srivastava et al., 2025).

These have implications for the practice of urban air-quality management. The city-specific and season-specific mitigation measures may yield better impact compared to a nation-wide mitigation measure, especially in winter and post monsoon. Combining meteorological monitoring with pollution monitoring could make it easier to give early warning, plan for the season and target emission control. But the data set used was limited for the secondary data and

the factors such as traffic, industrial emission, population density, and land-use were not included. Future studies need to incorporate longer monitoring duration and source-specific and urban-form indicators to further explain how the spatial and temporal pollutant variation occurs in Indian cities.

5. Conclusion

This study is an integrated assessment of spatial and temporal variation of urban air pollution and its meteorological association at all major cities in India. The results indicated marked variations between cities, with a few northern and highly urbanized areas having a relatively higher air-pollution load compared to many north-east, coastal and hill cities. The seasonal analysis also indicated that particulate pollution and AQI were generally higher during winter and post-monsoon seasons while the monsoon season experienced comparatively better air quality. The patterns validate that the geographical settings and seasonal atmospheric phenomena play an important role in the distribution of urban pollution in India. Besides, meteorological factors were found to be important in determining pollution variability. Humidity, dew point, wind gusts, precipitation and cloud cover were generally correlated with reduced particulate pollution and AQI, while atmospheric pressure was positively correlated with the major pollution indicators. Multivariate analysis also indicated the joint effect of the meteorological factors on $PM_{2.5}$, PM_{10} and AQI. The study suggests the value of a combined approach of spatial monitoring, seasonal assessment and meteorological information in urban air-quality management. Overall, city-specific, season-specific mitigation strategies, along with ongoing environmental monitoring and enhanced monitoring of the atmosphere, could help improve the control of pollution and sustainable environmental planning in cities throughout India.

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