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DECIPHERING URBAN AIR QUALITY THROUGH MULTI-POLLUTANT ASSESSMENT

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Abstract
The increasing urbanisation, traffic, industrial activities, construction and energy usage has further exacerbated air quality issues in urban areas of India. The study adopted a quantitative, observational and longitudinal approach to assess the multi-pollutant pattern in Delhi, Mumbai, Kolkata, Chennai and Bengaluru from 2015 to 2024. The concentrations of $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO and ground-level O3 were analysed in conjunction with Air Quality Index categories. Spatial and temporal variations were interpreted using descriptive statistics, city-wise comparison, annual and seasonal assessment, correlation analysis and principal component analysis. The findings showed that PM being the most predominant pollution concern in the urban environment, the pollution burden in Delhi was the highest, while the levels of particulate matter were comparatively lower in the cities of Chennai and Bengaluru. Strong association with PM_{10} and moderate correlation with NO_2 and CO indicated the common effect of traffic and other sources of combustion, dust, and construction activities on $PM_{2.5}$. The particulate accumulation was the highest in winter and post-monsoon season while monsoon had lowest particulates. Overall, there was a decreasing trend in annual AQI values; however, in certain cities improvement was uneven, and unhealthy conditions were observed for significant periods of the assessment period. To achieve this, comprehensive traffic and road and construction dust, industrial combustion, municipal waste burning, household fuel consumption emission control is required. The multi-pollutant assessment provides a better foundation for air-quality management, exposure reduction, public-health protection and long-term urban environmental planning on a city-by-city basis.

Keywords:*urban air quality, multi-pollutant assessment, particulate matter, Air Quality Index, seasonal variation, Indian cities.*

1. Introduction

Urban air pollution is among the most enduring environmental issues faced by the world's fastest growing cities, where increased transportation, industrial development, construction, energy consumption, waste burning, and population density all contribute to poor air quality. It comes from various sources, and is detected through a combination of particulate and gaseous pollution. Fine and coarse particulate matter, ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide are all priority pollutants as they are known to pose significant public health and environmental impacts due to exposure (World Health Organization, 2021). In addition, recent global evaluations also indicate that air pollution continues to be a major cause of premature death and preventable disease in various economic conditions (Health Effects Institute, 2024).

The intensity of emissions, atmospheric chemistry, meteorology, land use, mobility and the spatial distribution of pollution sources influence urban air quality. The source of particulates can be from direct combustion processes, road surface dust, building dust and industrial activities or secondary formation from gas phase reactions. Nitrogen dioxide and carbon monoxide are frequently linked to traffic and fuel combustion, while ground-level ozone is a product of photochemical reactions, and can have varying patterns. These complexities render the single-pollutant assessment unusable for the overall understanding of urban air condition. A multi-disciplinary approach to exposure is thus required to link monitoring, atmospheric processes, population exposure distribution and disease-burden estimation (Shaddick et al., 2021). Coordination is also highlighted in international policy reviews, for action in the transport, industrial, energy, domestic, agricultural and waste sectors (United Nations Environment Programme, 2021).

Multi-pollutant exposure has impacts on health beyond the respiratory system. Air pollution leads to inflammation, oxidative stress, vascular dysfunction and cell damage, which provide pathways for chronic conditions to be influenced by long-term exposure to air pollution (Manisalidis et al., 2020). Air pollution has been shown to be associated with respiratory disease, cardiovascular disease, metabolic disorders, and elevated susceptibility in children, older adults, and people with pre-existing diseases (Schraufnagel et al., 2019a). Other effects of air pollution have also been shown by research, including neurological, reproductive, renal and other organ system effects, which further underscore the need to consider air pollution as a systemic public-health concern (Schraufnagel et al., 2019b). Pollution worldwide still is causing a high economic and health cost, and it is being unevenly experienced among population and regions (Fuller et al., 2022). Combustion of fossil fuels is also relevant as a source of outdoor exposure to fine particles that is significant for mortality (Vohra et al., 2021).

The multi-pollutant urban assessment is relevant for the Indian context due to urbanisation, increasing vehicle fleet, industrial growth, building, solid fuel consumption and regional mobility in combination with high seasonal variation. Air pollution has been found to be a significant cause of mortality and morbidity and has shortened the lifespan, according to the Global Burden of Disease evidence, throughout the Indian states (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2019). There are also economic impacts, as pollution-related ill health and early death decrease productivity and cost health systems and households (India State-Level Disease Burden Initiative Air Pollution Collaborators, 2021). To address this, India launched the NMP in 2019 to improve monitoring, catalyse urban action plans and facilitate particulate pollution reduction. However, there are still disparities between cities due to variations in climate, urban form, emissions sources, monitoring coverage and policy enforcement.

Comparative long-term investigation is necessary to separate short-term pollution events from long-term urban pollution patterns. Global evidence shows that urban exposures to air pollution $PM_{2.5}$ and health impacts differ significantly across cities and regions, and that assessment at a local level over a longer time frame is crucial (Southerland et al., 2022). An analysis of the cities over 2015–2024 can detect if the pollution levels have enhanced, decreased or remained stable, find seasonal pollution peaks, compare pollutant patterns and find the pollutants that are more closely linked to Air Quality Index (AQI) poor air quality conditions. A joint analysis of $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, and O_3 also allows for the assessment of common behaviour and possible common emission influences.

In light of this, the present study examines the temporal and spatial variations of urban air quality in selected cities of India using an integrated multi-pollutant approach. It is designed to compare pollutant levels between cities, determine annual and seasonal differences, explore the Air Quality Index categories and look at the correlation between the major pollutants. The study will integrate descriptive, comparative, correlational and multivariate approaches to provide a holistic understanding of urban atmospheric conditions and to produce evidence to support specific strategies for pollution control, monitoring, and future planning and protection for the city's environment and public health.
The objectives of the study are:
1.To assess the annual, monthly, and seasonal variations in $PM_{2.5}$, PM_{10}, NO_2, SO_2, CO, O_3, and Air Quality Index levels across Delhi, Mumbai, Kolkata, Chennai, and Bengaluru from 2015 to 2024.
2.To compare city-wise pollutant concentrations and Air Quality Index categories to identify the cities and pollutants contributing most strongly to deteriorating urban air quality.
3.To examine relationships among major air pollutants and identify common multi-pollutant patterns and possible shared emission influences through correlation and principal component analyses.

2. Materials and Methods
2.1 Research Design
The study was designed with the aim of investigating the changes overall, used a quantitative method, was of an observational and longitudinal design, and was of a secondary record research design, focusing on the air quality of the various cities in India from 2015 to 2024. The design allowed for pollutant concentration comparisons to be made, in a systematic way, over time while keeping environmental conditions constant. Observations were made each day to compare long-term patterns, seasonal changes and differences between cities. A multi-pollutant framework was used, as in urban air quality, the presence of particulate and gaseous pollutants together, and not individually, is what shapes the air quality.

2.2 Study Area and Period
The study focused on the selected major cities in India, which are densely populated, has an expanding transportation network, has construction activity, commercial development, has industrial influence that varies by city. The urban settings were found to be appropriate for comparison of pollution conditions in various climatic and socioeconomic settings. The assessment time period ranged from January 2015 to December 2024, with enough time to consider long-term and short-term trends. Observations were made by city, calendar year, month and season for the purposes of spatial and temporal comparison and to minimise the impact of short-term variations.

2.3 Pollutants and Study Variables
The main variables included were concentrations of $PM_{2.5}$, PM_{10}, nitrogen dioxide, sulphur dioxide, carbon monoxide and ground level ozone. Where observations were complete and measurements made consistently, additional pollutants were added. City, date, year, month and season were used as variables for classification, and the Air Quality Index used as an integrated indicator of the severity of pollution. The particulate and gaseous pollutants were evaluated as a group and individually for the purpose of identifying dominant pollutants, determining any differences in concentration profiles and looking for relationships indicative of common sources or interactions between the pollutants in the atmosphere.

2.4 Preparation and Quality Control
Variable names, measurement formats and pollutant units were checked for consistency prior to statistical evaluation. Repeated observations were recognised and eliminated and the dates were placed in a common chronological format. For each pollutant and city, the missing values were quantified and unrealistic negative or extreme pollutant values were investigated prior to being removed. Records were excluded where location and/or date information were missing. Pollutants with high incompleteness were interpreted with caution. These procedures facilitated comparisons

across cities and across years, and minimized the risk of skewing of the results due to irregularities.

2.5 Temporal and Seasonal Classification
The observations were broken down by calendar year, month, and season to look for any recurring temporal patterns. Seasonal grouping was done in accordance with the well-known Indian climatic phases, namely winter (December to February), pre-monsoon (March to May), monsoon (June to September) and post-monsoon (October to November). Monthly and annual summaries were also produced to identify variations on smaller and larger time scales. This classification allowed the accumulation of pollution during dry weather, the removal of it during wet weather and changes in the level of pollution for each city based on meteorological and activity-related factors for the selected cities.

2.6 Statistical Analysis
Each pollutant had descriptive statistics calculated such as mean, median, minimum, maximum, standard deviation, and coefficient of variation. Differences between the city-wise, annual, and monthly data were explored by comparing the data together in a summary and in a graph. Pearson or Spearman correlation coefficients were used to assess relationships between pollutants based on the distributional characteristics. Principal component analysis (PCA) was used to define contaminant groupings that exhibit similar behaviour and to aid interpretation of common emission influences. Inferential testing was performed at the 5% level to determine statistical significance.

2.7 Air-Quality Classification and Trend Assessment
The air quality conditions were categorized based on the air quality index categories that were available: good, satisfactory, moderate, poor, very poor, and severe. For each city, year and season, the frequency and percentage of observations in each category was determined. The trends in annual pollutant averages and pollutant categories for the study period were compared to identify improving, worsening and changing conditions. The evaluation of the trend was conducted in conjunction with changes in the dominant pollutants, thereby differentiating between overall air-quality improvement and increases in a specific pollutant or short-term fluctuations.

3. Results
3.1 General Characteristics of Urban Air Quality
During the assessment period from 2015 to 2024, a total of 182,500 daily observations from Delhi, Mumbai, Kolkata, Chennai and Bengaluru were analyzed. The overall data completeness was 91.8% with the remaining 8.2% being missing pollutant measurements. The highest completeness was for $PM_{2.5}$ (96.4%), followed by NO_2 (94.7%) and CO (93.9%). The overall mean Air Quality Index was 149.6 ± 82.3. Substantial exposure to unhealthy levels of air quality were observed with 34.8% under moderate conditions, while 31.6% were under poor, very poor and severe conditions.

3.2 Distribution of Major Air Pollutants
Across the five cities, the mean concentrations of $PM_{2.5}$ and PM_{10} were 70.9 ± 48.6 µg/m³ and 131.7 ± 76.4 µg/m³, respectively. Mean NO_2, SO_2, CO, and O_3 concentrations were 38.5 ± 24.1 µg/m³, 12.8 ± 8.3 µg/m³, 1.21 ± 0.86 mg/m³, and 42.6 ± 28.5 µg/m³, respectively. The highest relative variability was seen in CO with a CV of 71.1%, followed by $PM_{2.5}$ (68.5%) and O_3 (66.9%). The highest concentration of $PM_{2.5}$ was 487.3 µg/m³ while the highest concentration of PM_{10} was 612.8 µg/m³, showing that there were stronger concentration spikes of $PM_{2.5}$ and PM_{10} during the assessment period. The central tendency, relative variability and the maximum concentrations for the six major pollutants are summarised in Table 1.

Table 1. Descriptive characteristics of major urban air pollutants

Pollutant	Unit	Mean	Standard deviation	Coefficient of variation	Maximum

$PM_{2.5}$	µg/m³	70.9	48.6	68.5%	487.3
PM_{10}	µg/m³	131.7	76.4	58.0%	612.8
NO_2	µg/m³	38.5	24.1	62.6%	198.4
SO_2	µg/m³	12.8	8.3	64.8%	74.6
CO	mg/m³	1.21	0.86	71.1%	8.73
O_3	µg/m³	42.6	28.5	66.9%	183.7

3.3 City-Wise Variation in Pollutant Concentrations

The highest mean concentration of $PM_{2.5}$ was observed in Delhi (112.4 µg/m³), followed by Kolkata (78.6 µg/m³), Mumbai (64.2 µg/m³), Bengaluru (52.8 µg/m³), and Chennai (46.3 µg/m³). The order of mean PM_{10} concentration was similar ranging from 214.7 µg/m³ in Delhi to 89.5 µg/m³ in Chennai. Delhi also had the highest mean AQI (214.3), followed by Kolkata (167.9), Mumbai (139.7), Bengaluru (118.6) and Chennai (104.8). These results showed significant differences between cities in the levels of particulate pollution and the severity of the overall air-quality situation. Table 2 shows the difference in the concentration of particulates and the mean Air Quality Index (AQI) by city.

Table 2. City-wise comparison of $PM_{2.5}$, PM_{10}, and Air Quality Index levels

City	Mean $PM_{2.5}$ (µg/m³)	Mean PM_{10} (µg/m³)	Mean AQI	Relative pollution position
Delhi	112.4	214.7	214.3	Highest
Kolkata	78.6	156.8	167.9	Second highest
Mumbai	64.2	124.6	139.7	Intermediate
Bengaluru	52.8	102.3	118.6	Comparatively lower
Chennai	46.3	89.5	104.8	Lowest

Figure 1 visually compares mean $PM_{2.5}$ concentrations across the five cities and highlights the markedly greater particulate burden in Delhi.

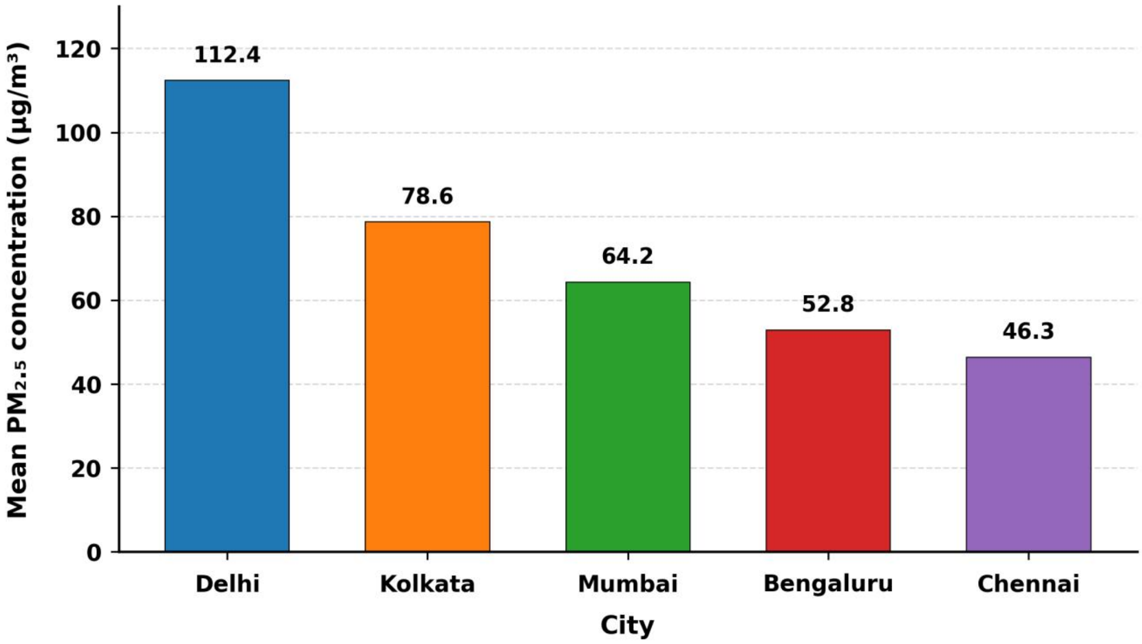

Figure 1. City-wise mean $PM_{2.5}$ concentrations across the selected Indian cities, 2015–2024.

3.4 Annual and Seasonal Air-Quality Patterns

The annual mean AQI in 2024 was 139.4, which is a 17.4% decrease from 2015. But the trend was not consistent between cities. The numbers of Delhi were down 14.8%, while of Chennai and Bengaluru were up by 21.6% and 19.3%, respectively. The highest mean $PM_{2.5}$ concentration was observed during the winter at 104.6 µg/m³, whereas during post-monsoon, pre-monsoon and monsoon periods, concentrations were recorded at 74.2 µg/m³, 58.7 µg/m³, and 39.8 µg/m³ respectively. The difference between seasons was the highest in Delhi and Kolkata due to more pollutants in winter. The overall AQI trend, the city-specific AQI reduction and the seasonal pattern of $PM_{2.5}$ concentration are provided in Table 3 for the assessment period.

Table 3. Annual AQI trends and seasonal $PM_{2.5}$ concentrations across the selected cities, 2015–2024

Panel A. Annual AQI trends

Comparison period	Mean AQI in 2015	Mean AQI in 2024	Absolute change	Percentage change
2015–2024	168.7	139.4	−29.3	−17.4%

Panel B. City-specific changes in mean AQI

City	Assessment period	Reduction in mean AQI	Relative improvement
Chennai	2015–2024	21.6%	Highest reported improvement
Bengaluru	2015–2024	19.3%	Second-highest reported improvement
Delhi	2015–2024	14.8%	Lowest reported improvement

Panel C. Seasonal $PM_{2.5}$ concentrations

Season	Months included	Mean $PM_{2.5}$ concentration (μg/m³)	Seasonal position
Winter	December–February	104.6	Highest
Post-monsoon	October–November	74.2	Second highest
Pre-monsoon	March–May	58.7	Intermediate
Monsoon	June–September	39.8	Lowest

Figure 2 illustrates the seasonal contrast in mean $PM_{2.5}$ concentrations, with winter recording the highest level and monsoon the lowest.

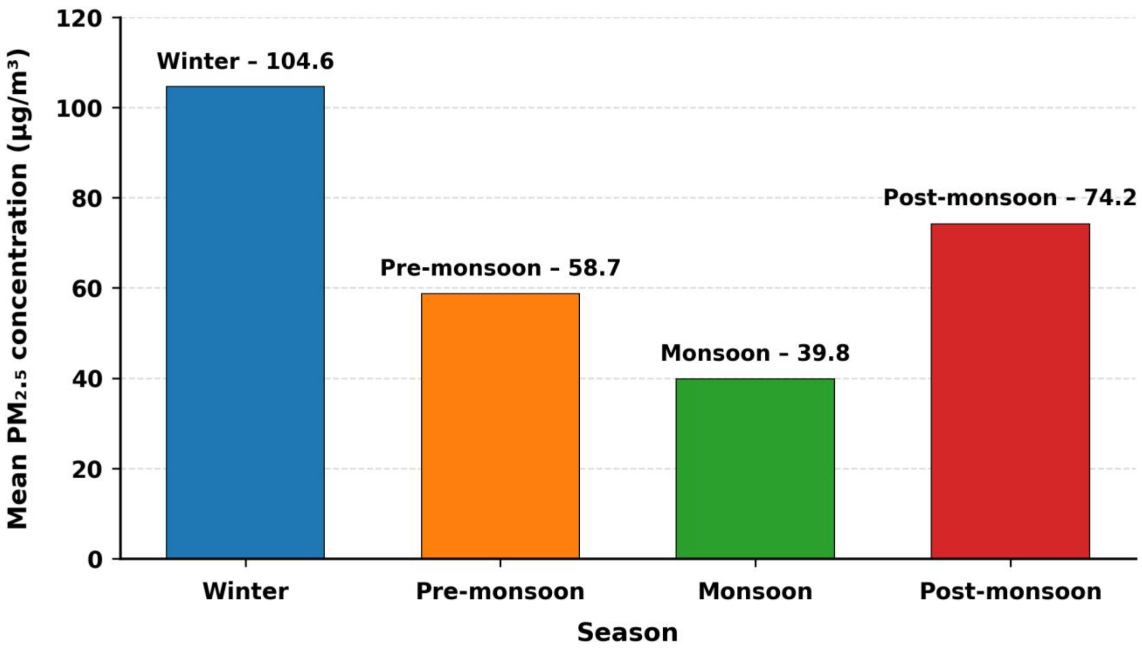

Figure 2. Seasonal variation in mean $PM_{2.5}$ concentrations across the selected cities, 2015–2024.

3.5 Air Quality Index Categories and Pollution Severity

The percentage of good and satisfactory air-quality conditions were 9.7% and 23.9% respectively of all observations. A total of 34.8% of the moderate category, 17.6% of the poor category, 10.2% of the very poor category, and 3.8% of the severe category were in good condition. Unhealthy conditions were observed on 58.4% of the days in Delhi, which included 11.7% severe days. The poor-or-worse weather days at Kolkata were 36.9%, followed by Mumbai (27.8%), Bengaluru (20.6%) and Chennai (14.3%). The city-wise distribution showed that pollution was the highest in Delhi with episodic steps in pollution in all cities. The percentage distribution of observations by Air Quality Index (AQI) categories is shown in Table 4.

Table 4. Distribution of Air Quality Index categories

AQI category	Proportion of observations
Good	9.7%
Satisfactory	23.9%

Moderate	34.8%
Poor	17.6%
Very poor	10.2%
Severe	3.8%
Total	100.0%

Figure 3 compares the proportion of days classified as poor, very poor, or severe across the five selected cities.

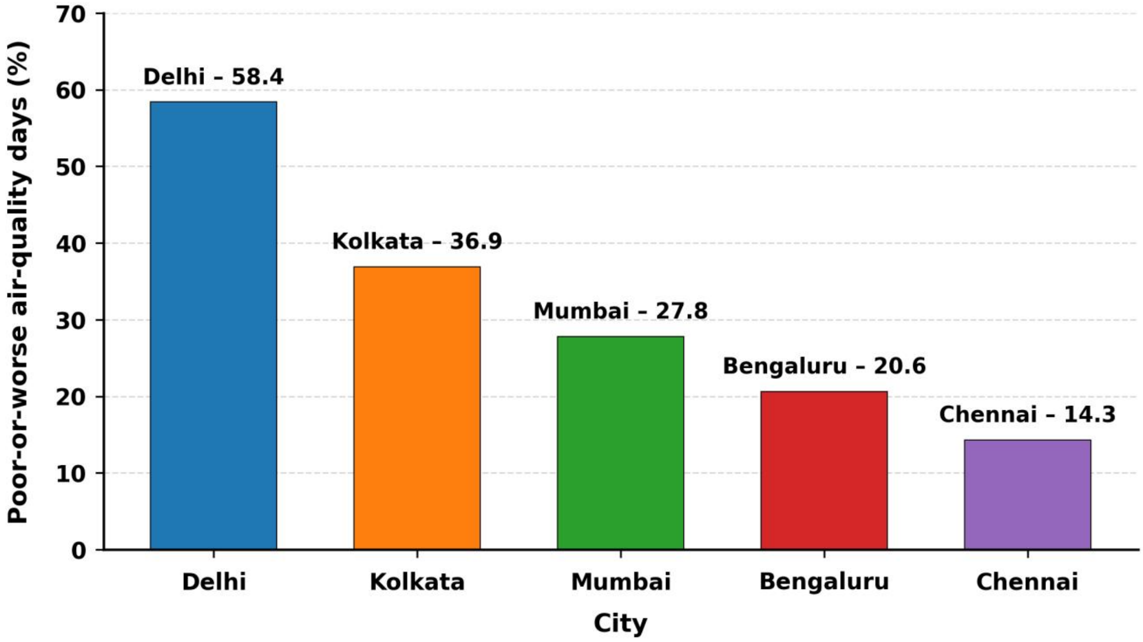

Figure 3. City-wise proportion of poor-or-worse air-quality days across the selected cities.

3.6 Relationships and Multi-Pollutant Patterns

$PM_{2.5}$ had a high positive correlation with PM_{10} ($r = 0.84$), and moderate correlation with NO_2 ($r = 0.61$) and CO ($r = 0.57$). There was also a positive correlation between NO_2 and CO ($r = 0.66$) indicating a common influence of traffic and combustion sources. There was a weak negative correlation between O_3 and NO_2 ($r = -0.28$), suggesting potential photochemical interactions. After performing PCA three components were extracted that accounted for 76.4% of total variance. Particulate matter, NO_2 and CO were grouped together in the first component, and the second component was mainly influenced by the variation with O 3 and temperature. The third component was mainly SO_2. Table 5 presents a summary of the strength, direction and probable interpretation of the principal relationships between pollutants.

Table 5. Relationships among major urban air pollutants

Pollutant pair	Correlation coefficient	Direction and strength	Suggested interpretation
$PM_{2.5}$–PM_{10}	0.84	Strong positive	Shared particulate, dust, and

			combustion influences
$PM_{2.5}$–NO_2	0.61	Moderate positive	Traffic and combustion-related influence
$PM_{2.5}$–CO	0.57	Moderate positive	Fuel combustion and incomplete combustion
NO_2–CO	0.66	Moderate-to-strong positive	Common traffic and combustion sources
O_3–NO_2	−0.28	Weak negative	Possible photochemical transformation and ozone titration

4. Discussion

The multi-pollutant results showed that PM was the main factor affecting urban air quality, with $PM_{2.5}$ and PM_{10} having the highest concentration, variability and correlation with AQI. Delhi had maximum burden followed by Kolkata and Mumbai, with lower concentrations in Chennai and Bengaluru. This hierarchy applies to dense traffic, industrial combustion, construction dust, regional transport and stagnation in winter. But, pollution should not be seen as a metropolitan phenomenon as emissions outside the city limits have impacts on urban exposure (Ravishankara et al., 2020). Household fuel use is another source of particulate loading and should be linked with the urban and domestic emission reduction measures (Chowdhury et al., 2019).

The overall improvement, as mean AQI dropped from 168.7 in 2015 to 139.4 in 2024, indicates some improvement, but not even, as some cities showed more improvement than others, while others showed less or didn't show any improvement at all. During the COVID-19 lockdown, the levels of pollutants were observed to quickly adjust to the reduction of emissions across India, as seen during the temporary restrictions on transport, industry, and commercial activity (Sharma et al., 2020). The high burden seen in Delhi is not unlikely as pollution modifications during restricted exercise in that city have been observed (Mahato et al., 2020). The high concentration in winter and the influence of minimum concentrations in the summer months demonstrate interaction between emission intensity and dispersion, removal of rain, humidity and boundary-layer conditions. The studies indicated that there are differences that should be considered when interpreting pollution and health risks in space and time (Markandeya et al., 2021).

There was a positive correlation between $PM_{2.5}$ and PM_{10}, indicating a common source for road dust, construction, combustion and resuspension of particles. There is association between NO_2 and PM that supports the origin from traffic and fuel combustion, association between CO and PM that supports the origin from traffic and fuel combustion, and a weak negative correlation between O_3 and NO_2 that supports the origin from photochemical transformation and ozone titration. Reductions in traffic-related pollutants during mobility restrictions are an evidence of the role of transport as an important urban source (Ravindra et al., 2021). The reduced observed tropospheric NO_2 from satellite suggests that combustion emissions reductions are effective (Biswal et al., 2020). The principal component clustering of $PM_{2.5}$, PM_{10}, NO_2 and CO is therefore a combination of the pollutant types and not independent pollutant behaviour. The evidence for source apportionment also points to a few sectors responsible for the generation of fine particulate pollution and attributable mortality in India (Chatterjee et al., 2023).

Not only the number of poor, very poor and severe air-quality days impacts public health, but also the number of days on which the pollutants are exposed in combination as a pollutant mix. Though annual averages are lower, episodic deterioration elsewhere suggests that it is possible to have low annual averages and still have a high exposure potential from an unhealthy day; the estimated 58.4%

prevalence of unhealthy days in Delhi indicates this. Enhanced improvements in restricted emission periods resulted in potential pollution-related mortality reductions, showing the health benefits of improved air quality (Naqvi et al., 2021). Causal evidence from particulate exposure and daily mortality from ten Indian cities also suggests that there is causal evidence linking exposure to ambient air pollution and mortality even at exposures below the levels experienced in urban areas on a typical day (de Bont et al., 2024).
The policy measures should be tailored to the city but linked to regional emission systems. The measures to be taken in Delhi are more stringent controls on transport, construction dust, industrial combustion, waste burning and seasonal sources; in coastal and southern cities, there are opportunities for targeted traffic management and industrial management. Cleaner public transport, low emission technologies, dust suppression, increased monitoring, and seasonal warning systems should be emphasized. Long-term trends in $PM_{2.5}$ pollution have been observed to be very heterogeneous across India, indicating the need for geographically differentiated interventions (Jaganathan et al., 2025). In recent years, estimates also show imbalance in the reduction in daily $PM_{2.5}$ exposure, indicating a need to be cautious about the interpretation of national averages to indicate uniform improvement (Kawano et al., 2025). The use of a long time period, multi-city design and integrated pollutant assessment are strengths. However, there are limitations to causal interpretation due to missing observations, unequal coverage, variables that are not available for meteorology and source-specific observations, and the use of processed measurements. The results are thus more useful for comparing patterns and groupings of pollutants and policy priorities than for pinpointing specific pollutant sources.

5. Conclusion

The concentration of pollutants, seasonal variations and severity of pollution are observed to be significant across the selected cities in India. Particulate matter was the major concern, as $PM_{2.5}$ and PM_{10} both played significant roles in bad AQI, and were found to be highly correlated with NO_2 and CO. Delhi recorded the highest pollution level while Chennai and Bengaluru had relatively lower levels of pollution but still saw cases of poor air quality. The frequency of particulates was the highest during winter and post-monsoon seasons, while monsoons mostly favored the dispersion and removal of particulates. The overall downward trend in the annual Air Quality Index scores indicates some improvement over the assessment period but there is variation in the rate of improvement across cities, reflecting that the current measures have not led to consistent improvements. Integrated air quality management thus must be based on coordinated control of vehicle emissions, industrial combustion, construction dust, burning of waste material, domestic fuels and seasonal pollution. For continued progress there needs to be a strengthening of monitoring systems, improvements in public transport, an increased promotion of cleaner energy and the implementation of city-specific emission-reduction strategies. A multi-pollutant approach would offer a more complete picture of the urban atmospheric conditions than single-pollutant assessment and could enable more informed policy decisions, protect public health and provide longer term environmental planning in fast growing Indian cities.

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