Meteorology-Driven Persistence of PM2.5 Pollution in Indian Cities: Implications for NCAP Phase-III

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Executive Summary

This report analyses how meteorological conditions influence the persistence of PM2.5 pollution across six major Indian cities like Delhi, Patna, Kolkata, Mumbai, Chennai, and Bengaluru, to inform Phase-III of the National Clean Air Programme (NCAP). Using CPCB air quality data (2024-2025) combined with meteorological clustering, the study distinguishes emission-driven pollution from weather-driven variability. Results show that northern Indo-Gangetic Plain cities experience severe winter pollution due to low wind speeds, high humidity, and atmospheric stagnation, with Delhi and Patna frequently exceeding national standards. In contrast, coastal and southern cities benefit from stronger ventilation and display comparatively stable and lower PM2.5 levels, though emerging winter deterioration is noted in Chennai and Mumbai. The findings reveal that meteorology can amplify or suppress pollution by up to 40%,

often masking true emission trends. The report recommends that NCAP Phase-III adopt season-specific, meteorology-adjusted evaluation frameworks, dynamic winter action plans, and regional airshed coordination to ensure realistic targets, better episode management, and more effective long-term air quality improvements.

1. Background

Fine particulate matter (PM2.5) is recognized as one of the most harmful air pollutants due to its ability to penetrate deep into the respiratory system, leading to severe health impacts including cardiovascular and respiratory diseases and premature mortality. In India, rapid urbanization, population growth, vehicular emissions, industrial activities, construction dust, and biomass burning have resulted in persistently high PM2.5 levels, particularly in metropolitan regions.

Despite the implementation of multiple air quality management programs, including the National Clean Air Programme (NCAP), several Indian cities continue to experience PM2.5 concentrations exceeding the National Ambient Air Quality Standards (NAAQS). A major challenge in assessing the effectiveness of emission-control measures under NCAP is the strong influence of meteorological conditions on observed PM2.5 concentrations. Meteorology affects pollutant dispersion, accumulation, chemical transformation, and regional transport, often causing large day-to-day and seasonal variability even under similar emission conditions. These factors complicate the direct attribution of air quality outcomes to policy interventions and highlight the need for a re-evaluation of planning and implementation strategies in upcoming phases of NCAP, particularly Phase III, to enhance its overall effectiveness.

Meteorological parameters such as wind speed (WS), wind direction (WD), relative humidity (RH), and temperature govern atmospheric ventilation, boundary-layer dynamics, and secondary aerosol formation. Low wind speeds and stable atmospheric conditions promote pollutant accumulation, while high humidity enhances hygroscopic growth of fine particles. Additionally, wind direction plays a critical role in regional pollutant transport, especially during winter and post-monsoon periods.

Given this strong meteorological modulation, conventional trend analysis alone may not adequately capture the true drivers of PM2.5 variability. Meteorology-based regime analysis provides a robust framework to disentangle emission-related changes from atmospheric influences by grouping days with similar meteorological conditions. Such an approach enables identification of pollution-prone weather regimes, seasonal transitions, and extreme pollution episodes, thereby improving the interpretation of air quality trends and policy outcomes.

In this study, we apply a comprehensive temporal and meteorology-based clustering framework to analyse daily PM2.5 variability over six major Indian cities-**Delhi, Patna, Chennai, Bengaluru, Mumbai, and Kolkata** covering different climatic zones of India. The analysis integrates station-averaged CPCB observations with meteorological clustering to characterize PM2.5 behaviour across monthly, seasonal, and regime-specific scales.

Why is a Meteorology-Adjusted Assessment of PM2.5 Needed?

Air quality assessments in India have traditionally relied on observed trends in ambient PM2.5 concentrations to evaluate the effectiveness of pollution control policies. While such trend-based analyses are useful, they can be misleading if meteorological influences are not explicitly accounted for. Variations in wind patterns, temperature, humidity, and boundary-layer dynamics can significantly alter pollutant dispersion and accumulation, often masking or exaggerating the apparent impact of emission-reduction measures.

For instance, a year with unfavourable meteorological conditions such as prolonged low wind speeds or enhanced atmospheric stability may exhibit elevated PM2.5 levels despite successful emission controls. Conversely, improved air quality observed during periods of strong ventilation or atypical weather may be incorrectly attributed to policy interventions. This confounding effect is particularly pronounced in India, where monsoon dynamics, winter inversions, regional transport, and diverse climatic regimes strongly modulate air pollution across seasons and regions.

In the context of the National Clean Air Programme (NCAP), especially as India transitions toward Phase-III implementation, there is a growing need for evaluation frameworks that distinguish between meteorology-driven variability and emission-driven changes. Meteorology-adjusted analysis allow for a more objective assessment of policy effectiveness, identification of pollution-prone weather regimes, and improved targeting of sectoral and seasonal interventions.

This report is intended to support policymakers, air quality regulators, urban planners, and implementing agencies by providing a meteorology-informed perspective on PM2.5 persistence across major Indian cities. By highlighting when and where pollution is driven primarily by atmospheric conditions rather than emissions alone, the analysis offers actionable insights for designing realistic air quality targets, improving episode-based management strategies, and strengthening the scientific basis of NCAP Phase-III planning.

2. Data and Methodology

This report adopts an integrated observational and meteorology-based analytical framework to examine the persistence of PM2.5 pollution across selected Indian cities. Daily PM2.5 concentrations derived from CPCB monitoring stations are analysed alongside key meteorological parameters-wind speed, wind direction, relative humidity, and temperature to distinguish emission-driven pollution from weather-induced variability.

The analysis proceeds in three stages:

(i) Characterization of PM2.5 variability across monthly, seasonal, and annual timescales;

(ii) Assessment of compliance with national air quality standards;

(iii) Identification of dominant meteorological regimes using clustering techniques. By grouping days with similar meteorological conditions and linking them to observed PM2.5 levels, the methodology explicitly controls for atmospheric influences on air quality.

This approach enables a more robust comparison of pollution behaviour across cities and seasons and supports an objective interpretation of air quality trends relevant for policy evaluation under NCAP.

2.1 Study Area

The selected cities represent diverse geographical and climatic settings:

- **Delhi and Patna:** Indo-Gangetic Plain, severe winter pollution
- **Mumbai and Chennai:** Coastal urban environments with marine influence
- **Kolkata:** Lower Indo-Gangetic Plain urban environment
- **Bengaluru:** Inland southern peninsular city with relatively stronger ventilation

This selection allows inter-city comparison of PM2.5 behaviour under contrasting meteorological regimes.

2.2 Air Quality Data

Daily PM2.5 data were obtained from the Central Pollution Control Board (CPCB) online portal, which provides measurements from Continuous Ambient Air Quality Monitoring Stations (CAAQMS).

- Study period: January 2024 to December 2025
- Temporal resolution: Daily averages
- Pollutant analysed: PM2.5 (µg/m^3)

For each city:

1. PM2.5 data were extracted for all operational monitoring stations
2. Quality control checks were applied to remove missing and invalid values
3. A city-wide daily mean PM2.5 concentration was calculated by averaging across all available stations
4. Days with insufficient station coverage were excluded to maintain data reliability

This approach ensures that the PM2.5 time series represents city-scale air quality rather than site-specific behaviour.

2.3 Meteorological Data

Meteorological variables were compiled from station-level or nearest available meteorological observations corresponding to each city. The following parameters were used:

- Wind Speed (WS, m/s)

- Wind Direction (WD, degrees)
- Relative Humidity (RH, %)
- Temperature (°C), where available
- To ensure methodological consistency, clustering inputs were standardized for each city prior to analysis.

2.4 Temporal Analysis of PM2.5

Multiple temporal scales were examined to characterize $PM_{2.5}$ variability:

2.4.1 Monthly Distribution

Monthly PM2.5 distributions were analysed using boxplots to capture:

- Median concentration
- Interquartile range
- Extreme pollution events
- Seasonal variability

2.4.2 Seasonal and monthly Analysis

Daily PM2.5 data were converted monthly and grouped into four climatological seasons:

- **Winter (DJF)**
- **Summer (MAM)**
- **Monsoon (JJAS)**
- **Post-monsoon (ON)**

Seasonal and monthly mean PM2.5 concentrations were calculated to assess large-scale seasonal and month contrasts.

2.4.3 Annual Mean PM2.5

Annual average PM2.5 concentrations were computed for inter-annual comparison and contextualization against national standards.

2.5 Compliance with National Ambient Air Quality Standards

Compliance with the Indian NAAQS for PM2.5 ($\leq$ 60 µg/m³) was evaluated monthly.

The compliance percentage was calculated as:

$$Compliance\ (\%) = \frac{Number\ of\ days\ with\ PM_{2.5}\ \leq\ 60\ \mu g/m^3}{Total\ valid\ days} \times 100$$

Heatmaps were used to visualize monthly and inter-annual compliance patterns for each city.

2.6 Meteorology-Based Clustering

2.6.1 Clustering Technique

Meteorological regimes were identified using the K-means clustering algorithm, applied to daily meteorological variables.

- Input features: WS, WD, RH and temperature (where available)
- Data standardization: Z-score normalization

2.6.2 Selection of Optimal Clusters

The Silhouette Score was used to determine the optimal number of clusters. Across most cities, four clusters were found to best represent distinct meteorological regimes, capturing a balance between intra-cluster similarity and inter-cluster separation.

2.6.3 Meteorological regime interpretation

Across all cities, the K-means clustering applied to wind speed (WS), wind direction (WD), temperature (TEMP), and relative humidity (RH) resulted in four statistically distinct meteorological regimes. Although the absolute meteorological values vary by city, the relative behaviour of the clusters is consistent, allowing the clusters to be interpreted using a common qualitative framework. Accordingly, the clusters are labelled as follows:

- **Cluster 0** Cold-Humid-Low Wind:
  Characterized by relatively lower temperatures, high relative humidity, and weak wind speeds, this regime is strongly associated with pollutant accumulation and elevated PM2.5 concentrations, particularly in inland and northern cities.
- **Cluster 1** Dry-Moderate Wind:
  This regime exhibits moderate wind speeds, lower humidity, and comparatively better dispersion conditions, resulting in moderate PM2.5 levels. It often represents transition seasons such as pre-monsoon or post-monsoon periods.
- **Cluster 2** Warm-Humid-Stagnant:
  Defined by higher temperatures, high humidity, and low to moderate wind speeds, this regime favours secondary aerosol formation and moisture-driven particle growth, leading to elevated PM2.5, especially in humid and urban environments.
- **Cluster 3** Ventilated-Cleaner:
  This regime is marked by higher wind speeds, improved atmospheric mixing, and relatively lower PM2.5 concentrations, corresponding to cleaner air conditions, commonly observed during monsoon or high-ventilation periods.

2.7 Linking PM2.5 with Meteorological Regimes

Each daily PM2.5 observation was assigned to its corresponding meteorological cluster. This enabled:

- Quantification of PM2.5 statistics (mean, median, frequency) for each regime

- Identification of pollution-enhancing and pollution-dispersive meteorological conditions
- Analysis of seasonal dominance of specific regimes
  Time-series plots with cluster overlays were used to examine regime transitions and extreme pollution episodes.

3. Result

3.1 Monthly Distribution for each city

The monthly PM2.5 box plots show a pronounced winter pollution dominance across all cities, but with large differences in magnitude. Delhi and Patna stand out with extremely high winter medians and wide spreads, indicating frequent and severe pollution episodes. In contrast, Bengaluru and Chennai exhibit much lower median concentrations and narrower interquartile ranges, suggesting relatively cleaner air and more stable conditions throughout the year. The monsoon months (July–August) consistently correspond to the lowest PM2.5 levels across all cities, with reduced variability.

A second major observation is the difference in variability among cities. Northern and eastern cities (Delhi and Patna) show large month-to-month and within-month variability, especially during winter, with several extreme outliers. Coastal and southern cities (Chennai and Mumbai) show moderate variability, while Bengaluru remains the least variable city across most months. This indicates either stronger local emission control measures or more favourable dispersion conditions in southern regions

Delhi
Delhi records the highest PM2.5 concentrations throughout the year. Median values remain very high in winter months (November, December, and January), with multiple extreme outliers exceeding typical pollution thresholds, reflecting severe air quality episodes. Although concentrations decline during summer and monsoon months (June–August), the median values remain higher than those of other cities, indicating persistent pollution even in cleaner seasons.

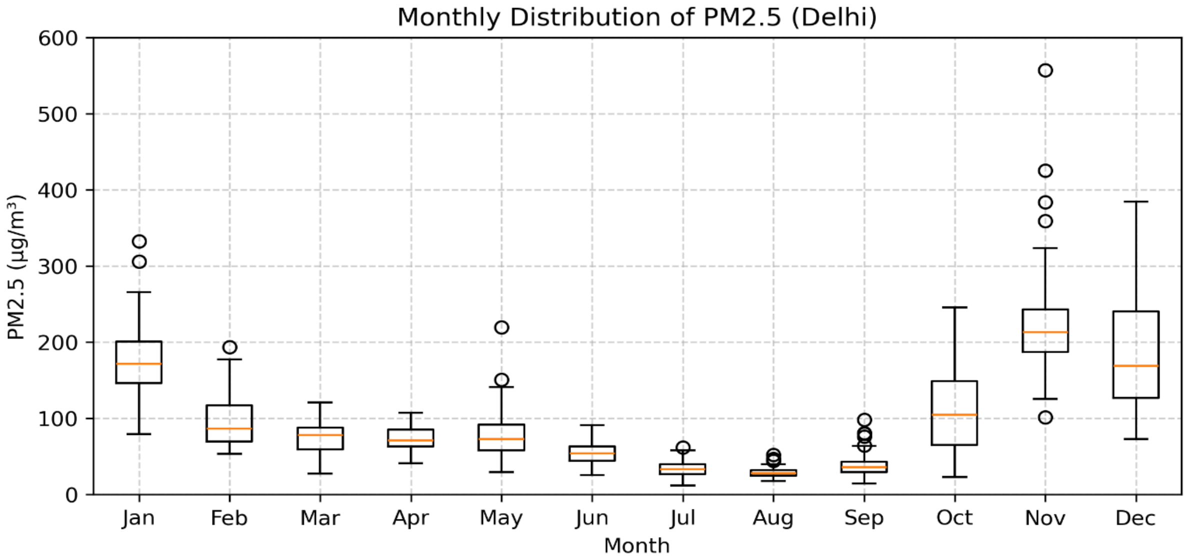

Figure-1: Monthly distribution of PM2.5 for Delhi city.

Bengaluru

Bengaluru shows consistently low PM2.5 levels compared to other cities. Median concentrations remain relatively stable, with only a slight increase during winter months. The narrow interquartile ranges across most months indicate low variability and fewer extreme pollution events, making Bengaluru the least polluted city among those analysed.

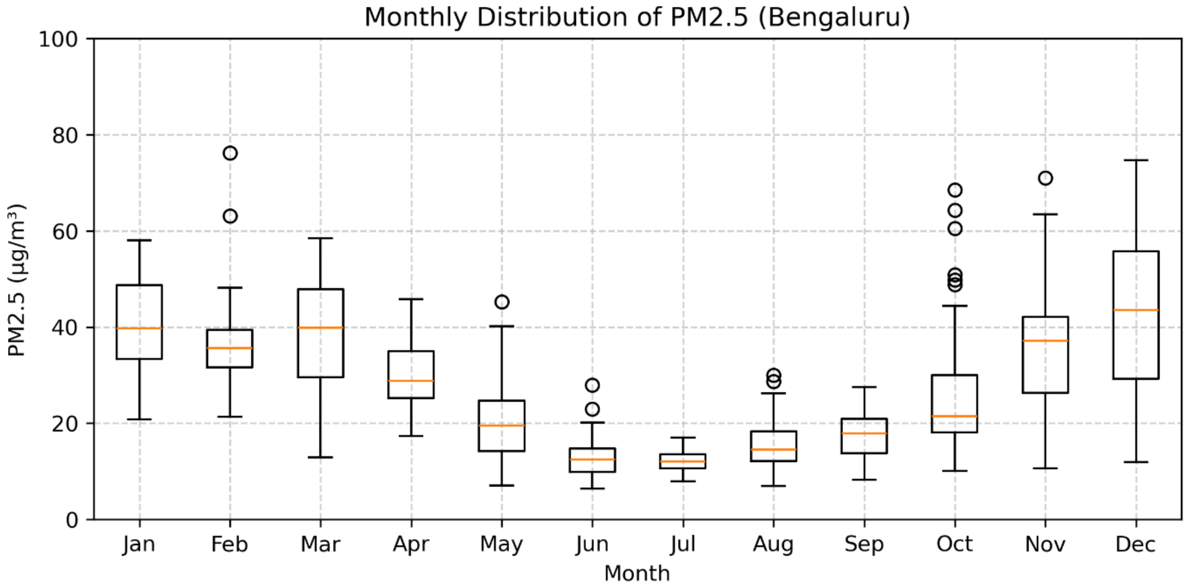

Figure-2: Monthly distribution of PM2.5 for Bengaluru city.

Chennai

Chennai exhibits moderate PM2.5 concentrations with noticeable seasonal variation. Higher medians are observed during winter and post-monsoon months, while summer and monsoon periods show reduced levels. Occasional high outliers suggest short-term pollution episodes, but overall concentrations remain lower than in northern cities.

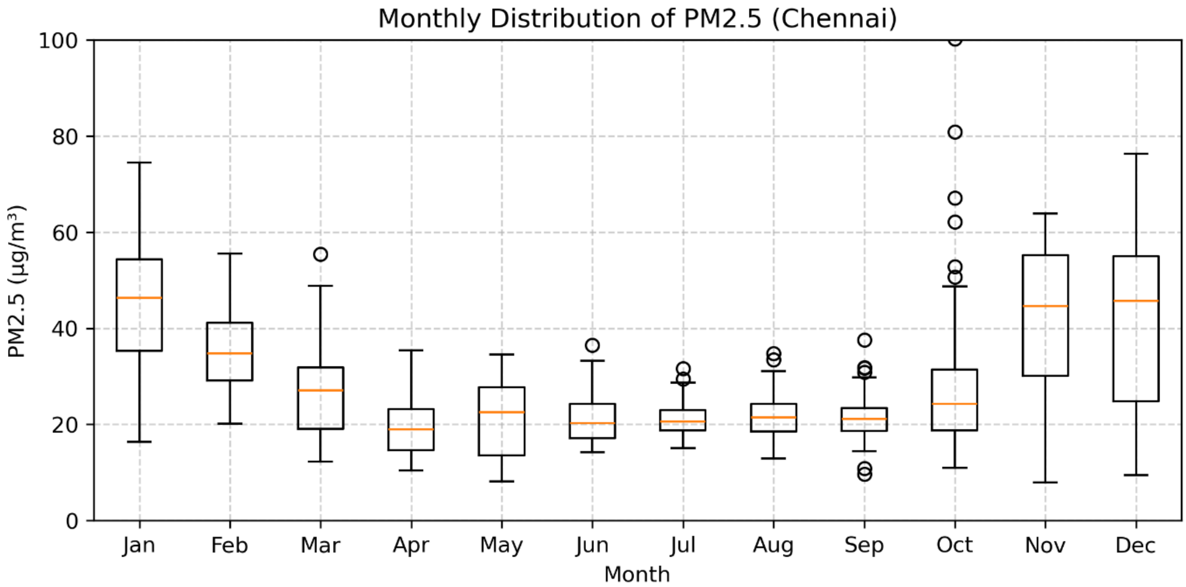

Figure-3: Monthly distribution of PM2.5 for Chennai city.

Kolkata

Kolkata shows moderate-to-high PM2.5 levels, particularly during winter months, though not as extreme as Delhi or Patna. The box plots indicate increased variability during winter, with elevated upper whiskers and outliers, while monsoon months show lower medians and tighter distributions.

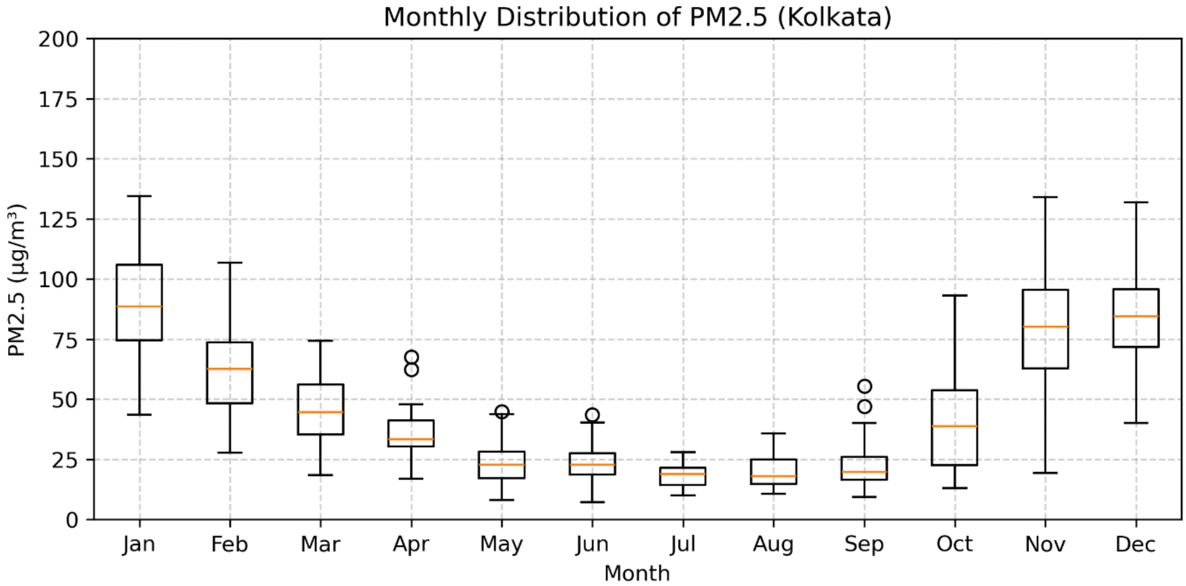

Figure-4: Monthly distribution of PM2.5 for Kolkata city.

Mumbai

Mumbai displays moderate pollution levels with a clear seasonal pattern. Winter months show higher medians and increased variability, while monsoon months exhibit sharp reductions in PM2.5. Despite being a coastal city, occasional high outliers during winter suggest the influence of local emissions and meteorological stagnation.

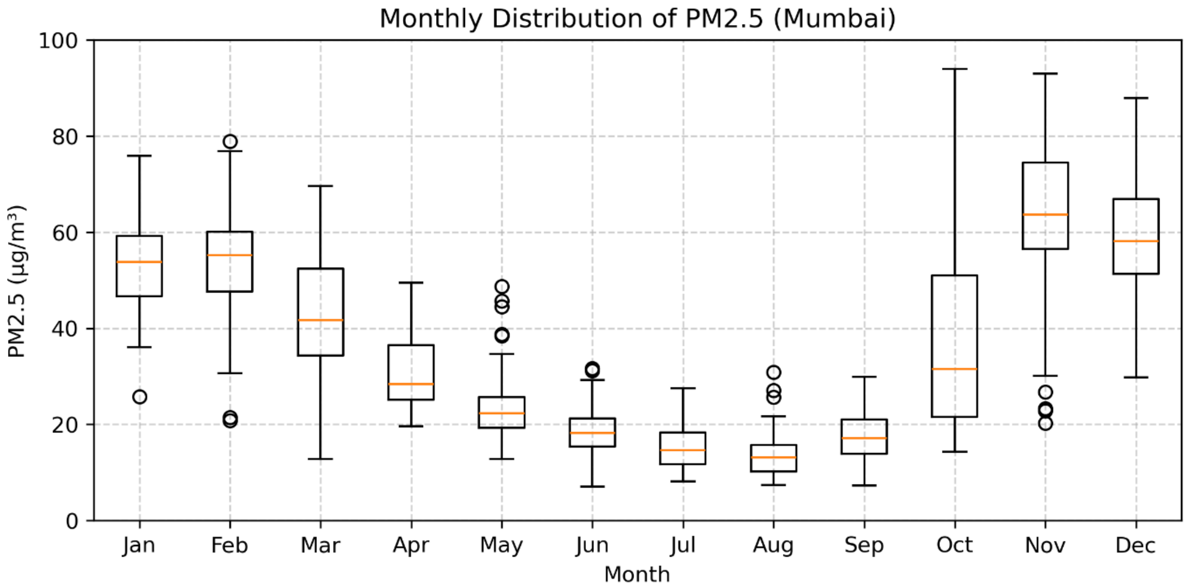

Figure-5: Monthly distribution of PM2.5 for Mumbai city.

Patna

Patna experiences persistently high PM2.5 concentrations, second only to Delhi. Winter months show very high medians and wide interquartile ranges, indicating frequent severe pollution events. Although concentrations decrease during monsoon months, the median values remain higher than those observed in most other cities, highlighting chronic air quality challenges in the region.

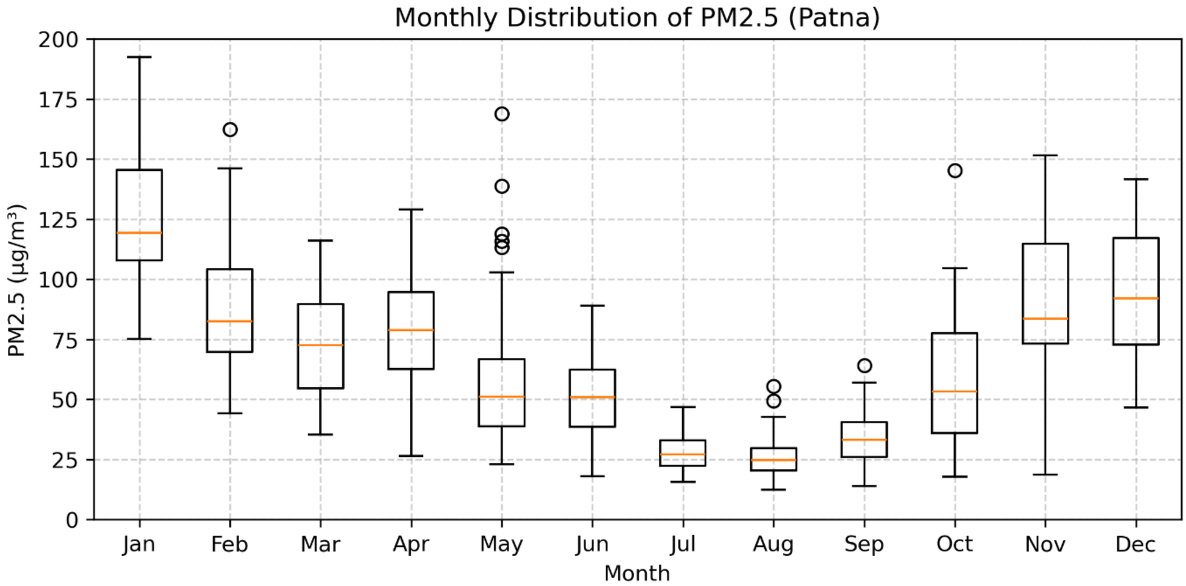

Figure-6: Monthly distribution of PM2.5 for Patna city.

3.2 Monthly and seasonal mean for each city

For Delhi:

The seasonal mean PM2.5 concentrations in Delhi show a clear persistence of severe air pollution across both years, with some improvement in 2025. In 2024, the seasonal mean values were 153.9 μg/m³ in winter (DJF), 80.0 μg/m³ in summer (MAM), 41.0 μg/m³ during the monsoon (JJAS), and the highest level of 174.9 μg/m³ in the post-monsoon season (ON). In 2025, winter pollution remained similarly high at 155.7 μg/m³, while summer and monsoon means declined to 71.1 μg/m³ and 35.9 μg/m³, respectively. A notable improvement is seen in the post-monsoon season, where the mean dropped from 174.9 μg/m³ in 2024 to 156.8 μg/m³ in 2025, indicating reduced pollution intensity after the monsoon compared to the previous year.

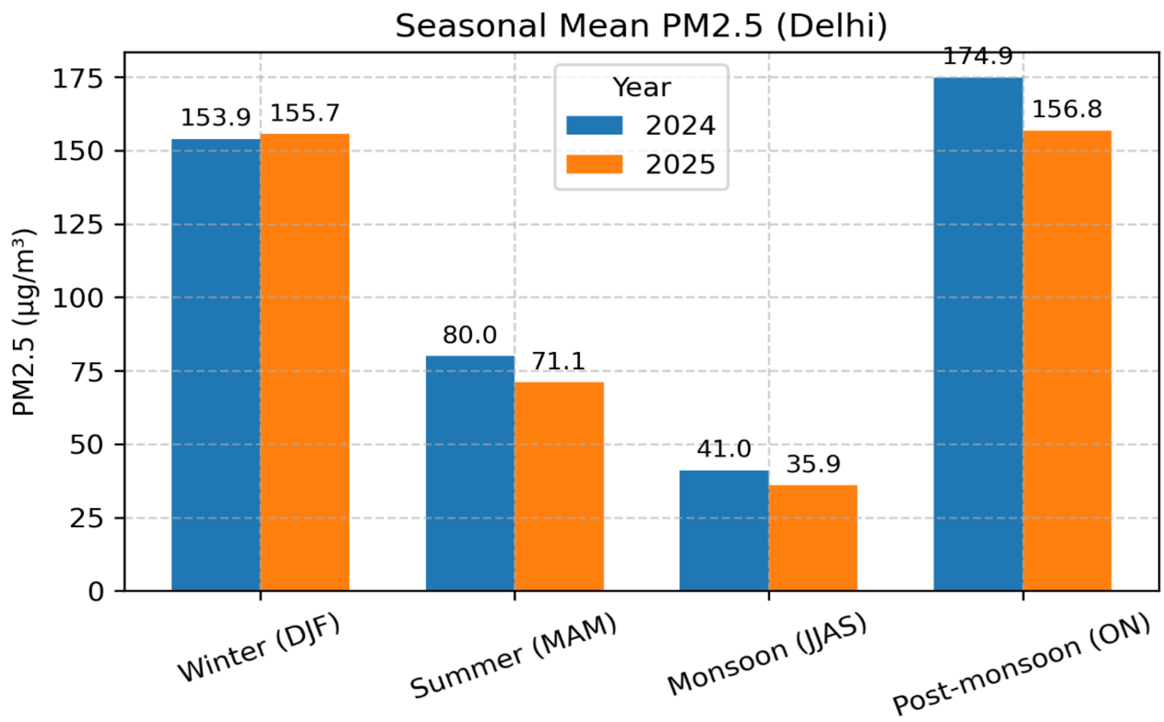

Figure-7: Seasonal Bar plot of PM2.5 for Delhi city.

The monthly average PM2.5 data further highlights these trends in detail. In 2024, the highest monthly mean occurred in November (242.1 µg/m³), followed by January (194.9 µg/m³) and December (164.3 µg/m³), reflecting extreme winter pollution. The cleanest period was August (26.2 µg/m³), with consistently lower values during July-September. In 2025, overall monthly means were lower for most months: January averaged 158.0 µg/m³, November 209.9 µg/m³, and December 206.6 µg/m³, all reduced compared to 2024 except December. The lowest monthly mean again occurred during the monsoon, with July at 28.6 µg/m³ and August at 32.1 µg/m³. Overall, the mean values suggest moderate improvement in air quality in 2025, especially during summer and post-monsoon months, though pollution levels remain far above safe limits in winter.

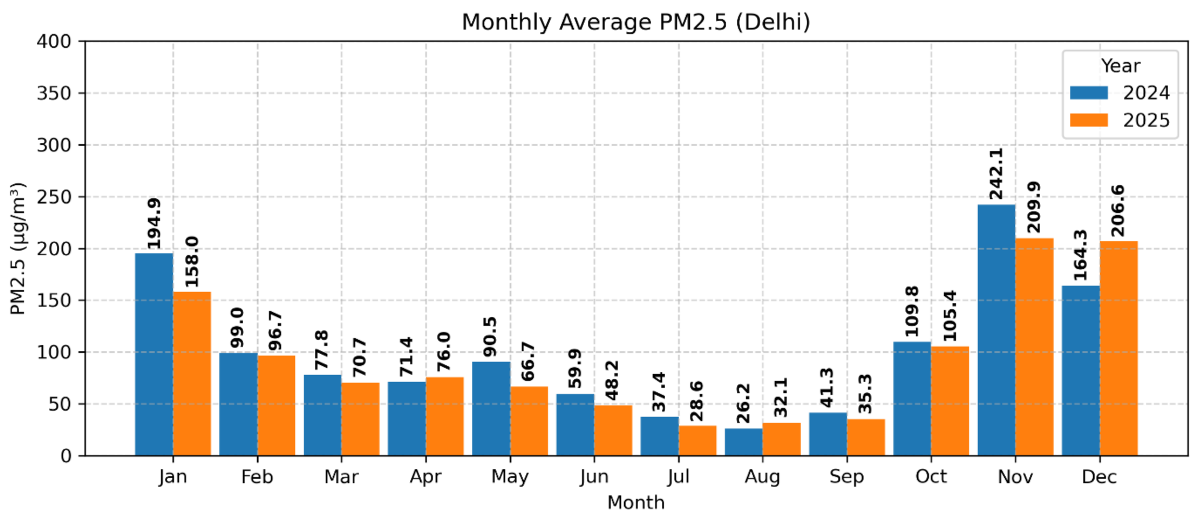

Figure-8: Monthly Bar plot of PM2.5 for Delhi city.

For Bengaluru:

The seasonal mean PM2.5 concentrations in Bengaluru indicate comparatively better air quality than northern cities, with clear seasonal variability across both years. In 2024, the seasonal mean values were 37.4 µg/m³ in winter (DJF), 35.7 µg/m³ in summer (MAM), 15.7 µg/m³ during the monsoon (JJAS), and 33.3 µg/m³ in the post-monsoon season (ON). In 2025, winter pollution increased to 42.4 µg/m³, indicating slightly poorer air quality during colder months, while significant improvements were observed in other seasons. The summer mean dropped sharply to 24.7 µg/m³, the monsoon mean declined further to 13.4 µg/m³, and the post-monsoon mean reduced to 28.6 µg/m³, reflecting overall seasonal improvement outside winter in 2025.

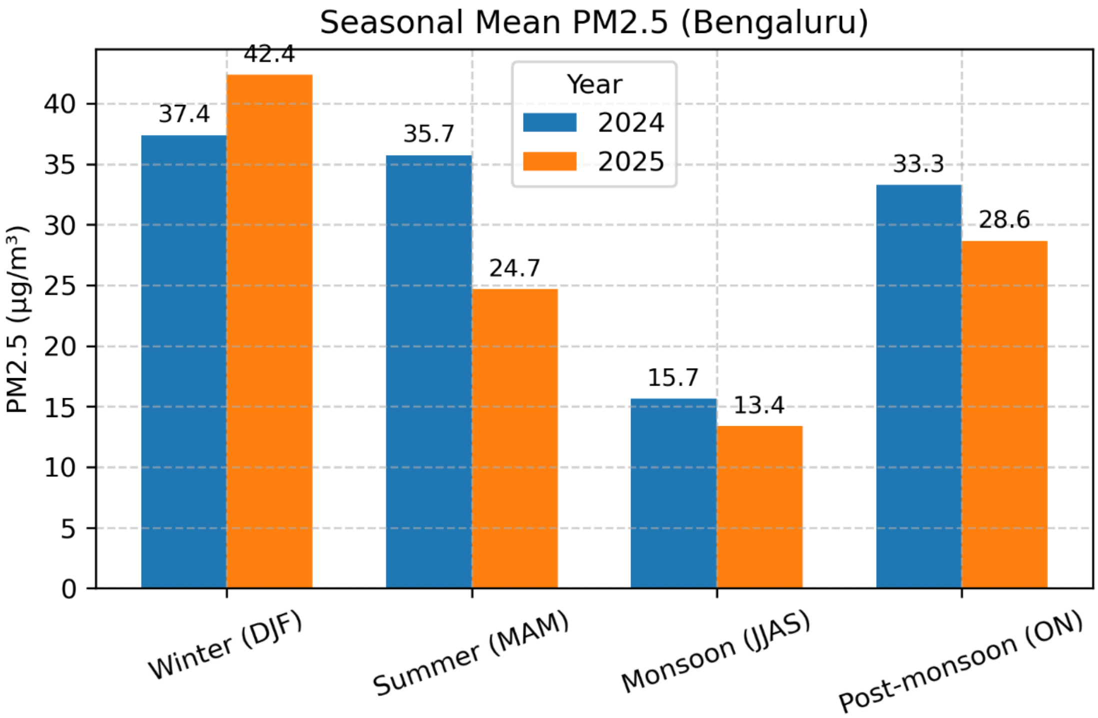

Figure-9: Seasonal Bar plot of PM2.5 for Bengaluru city.

The monthly average PM2.5 values further illustrate these patterns in detail. In 2024, the highest monthly mean was observed in March (46.2 µg/m³), followed by January (39.6 µg/m³) and February (39.4 µg/m³), while the cleanest months were June and July (both ~11-12 µg/m³) due to monsoon influence. In 2025, most months recorded lower mean values compared to 2024, particularly in April (26.9 µg/m³) and May (15.2 µg/m³). However, winter months showed mixed trends, with January (40.4 µg/m³) remaining high and a sharp increase in December (52.2 µg/m³), the highest monthly mean across both years. Overall, the mean PM2.5 levels suggest that Bengaluru experienced cleaner air in 2025 during summer, monsoon, and post-monsoon seasons, although episodic winter pollution remains a concern.

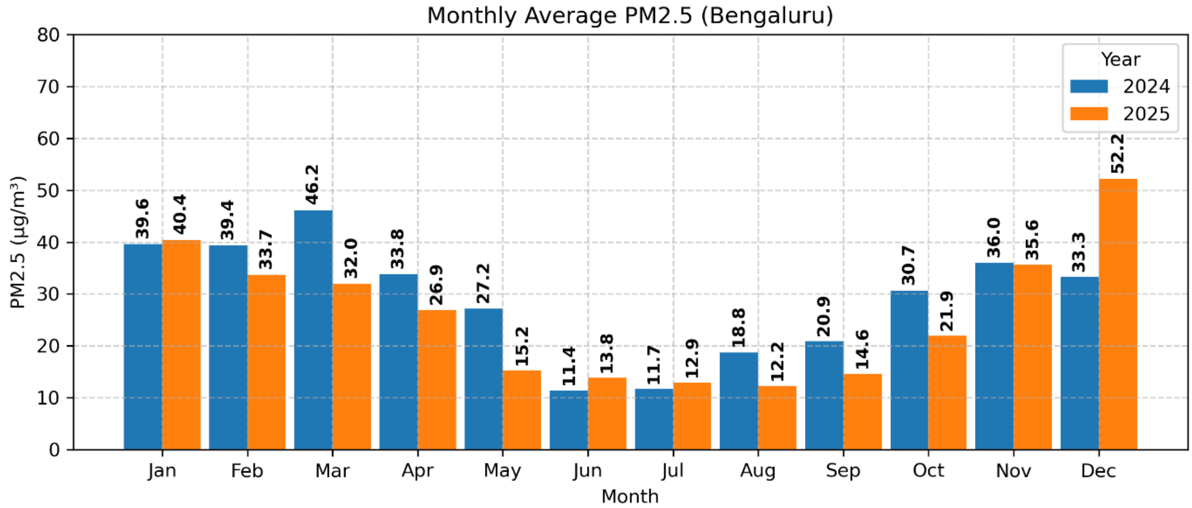

Figure-10: Monthly Bar plot of PM2.5 for Bengaluru city.

For Chennai:

The seasonal mean PM2.5 concentrations in Chennai indicate moderate air pollution levels with noticeable seasonal contrasts across both years. In 2024, the seasonal mean values were 37.8 µg/m³ during winter (DJF), 21.3 µg/m³ in summer (MAM), 21.2 µg/m³ during the monsoon (JJAS), and 34.1 µg/m³ in the post-monsoon season (ON). In 2025, seasonal means increased across all seasons, most notably in winter. Winter PM2.5 rose to 45.7 µg/m³, while summer increased slightly to 23.9 µg/m³. The monsoon season remained relatively stable at 21.5 µg/m³, and the post-monsoon mean increased to 36.0 µg/m³. Overall, Chennai experienced higher seasonal mean PM2.5 levels in 2025, with winter showing the most pronounced deterioration in air quality.

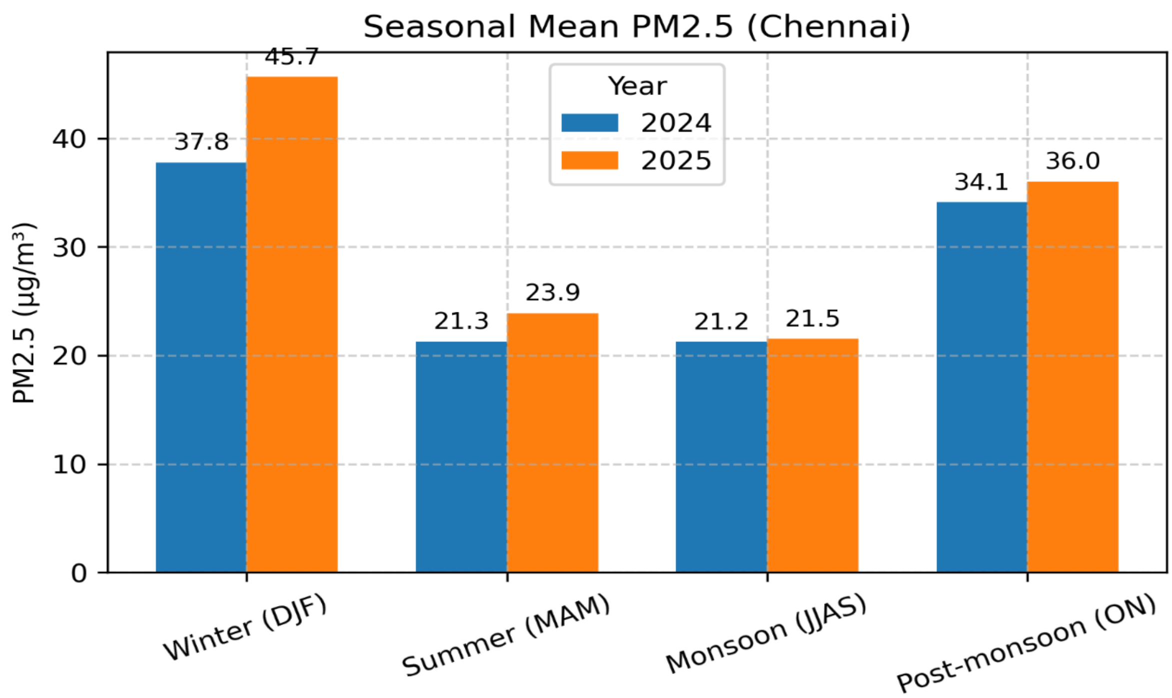

Figure-11: Seasonal Bar plot of PM2.5 for Chennai city.

The monthly average PM2.5 values provide further insight into intra-annual variability. In 2024, the highest monthly mean was observed in January (46.7 µg/m³), followed by November (39.6 µg/m³) and December (31.0 µg/m³), while the lowest levels occurred in May (16.5 µg/m³). In 2025, winter and post-monsoon months showed marked increases, with December recording the highest monthly mean of 53.7 µg/m³, the highest across both years. Other elevated months included January (46.8 µg/m³) and November (43.5 µg/m³). Summer and monsoon months showed relatively smaller fluctuations, remaining mostly within the 20-26 µg/m³ range. Overall, the mean monthly patterns suggest that Chennai's air quality worsened in 2025, particularly during winter and late post-monsoon months, while remaining comparatively cleaner during summer and monsoon periods.

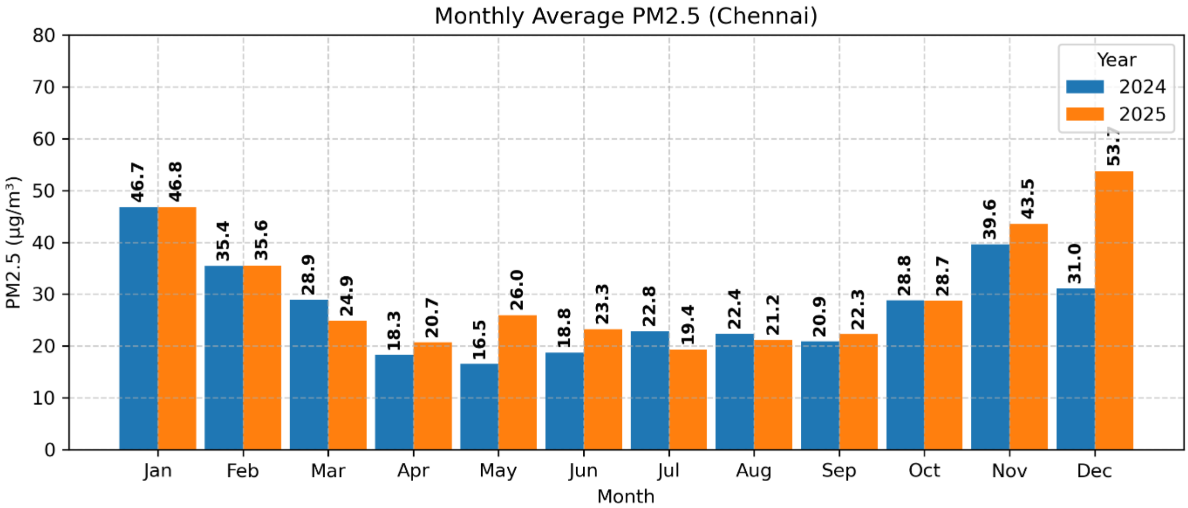

Figure-12: Monthly Bar plot of PM2.5 for Chennai city.

For Kolkata:

The seasonal mean PM2.5 concentrations in Kolkata show clear seasonal contrasts, with winter and post-monsoon periods experiencing higher pollution levels in both years. In 2024, the seasonal mean PM2.5 was highest in winter (DJF) at 80.9 µg/m³, followed by the post-monsoon season (ON) at 54.2 µg/m³. Summer (MAM) recorded a moderate mean of 35.1 µg/m³, while the lowest levels occurred during the monsoon (JJAS) at 20.3 µg/m³, reflecting the cleansing effect of rainfall. In 2025, winter pollution showed a slight improvement, decreasing to 77.2 µg/m³, and summer also declined marginally to 33.9 µg/m³. However, monsoon PM2.5 increased slightly to 21.7 µg/m³, and the post-monsoon mean rose noticeably to 62.0 µg/m³, indicating worsening air quality during late-year months in 2025 compared to 2024.

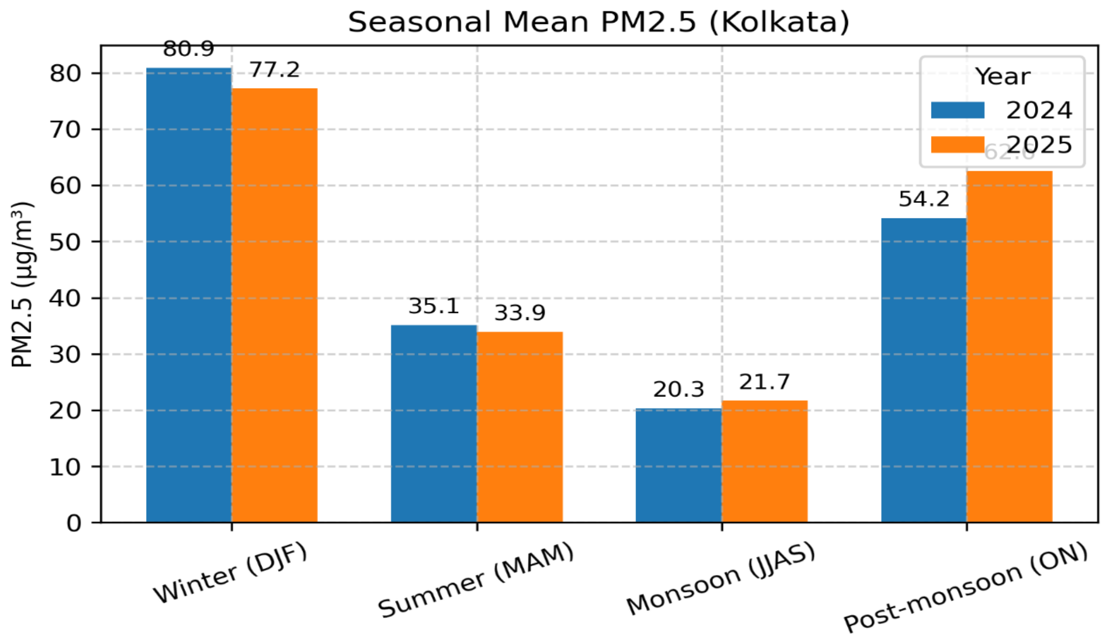

Figure-13: Seasonal Bar plot of PM2.5 for Kolkata city.

The monthly average PM2.5 patterns further illustrate these seasonal dynamics. In 2024, the highest monthly mean was observed in January (99.7 µg/m³), followed by February (68.5 µg/m³) and December (73.8 µg/m³), highlighting severe winter pollution episodes. The cleanest month was July (16.6 µg/m³) during the monsoon period. In 2025, most winter and post-monsoon months showed higher variability, with December reaching 95.7 µg/m³, the highest monthly mean of the year, and November averaging 82.1 µg/m³. Summer and monsoon months generally remained within the 18-46 µg/m³ range, with relatively stable conditions. Overall, the mean values suggest that while winter air quality improved slightly in 2025, post-monsoon pollution intensified in Kolkata, making late autumn and early winter the most critical periods for air quality management.

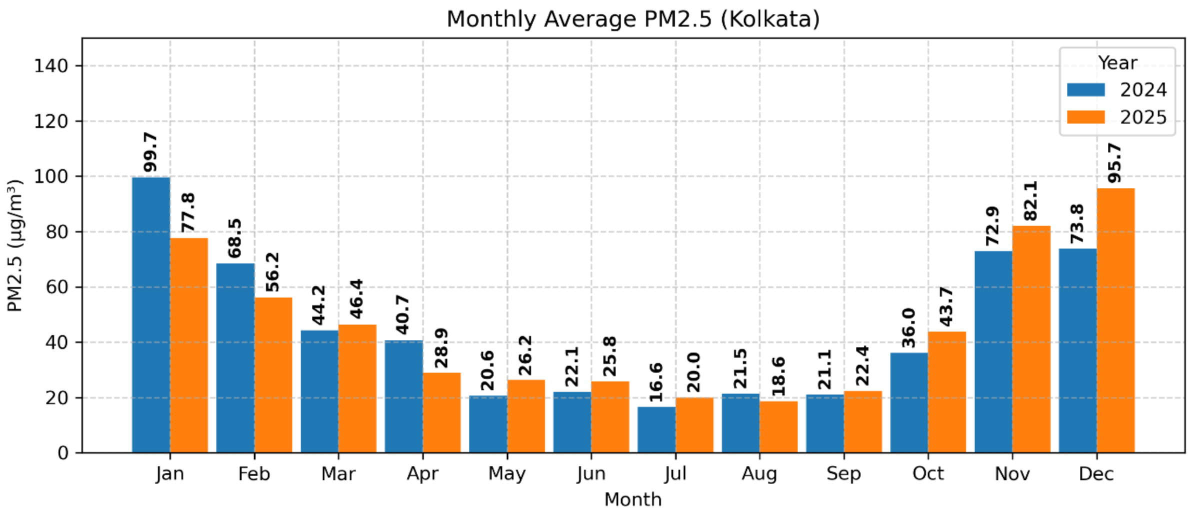

Figure-14: Monthly Bar plot of PM2.5 for Kolkata city.

For Mumbai:

The seasonal mean PM2.5 concentrations in Mumbai show moderate pollution levels with clear seasonal variation across both years. In 2024, the highest seasonal mean was recorded in winter (DJF) at 56.6 µg/m³, followed by the post-monsoon season (ON) at 49.2 µg/m³, indicating poorer air quality during cooler and transition months. Summer (MAM) had a mean of 30.4 µg/m³, while the lowest concentrations occurred during the monsoon (JJAS) at 14.9 µg/m³, reflecting the strong cleansing effect of rainfall. In 2025, winter PM2.5 declined slightly to 53.8 µg/m³, suggesting marginal improvement, whereas summer and monsoon means increased to 35.1 µg/m³ and 17.7 µg/m³, respectively. The post-monsoon mean also rose to 53.6 µg/m³, indicating a noticeable deterioration in air quality during late-year months in 2025 compared to 2024.

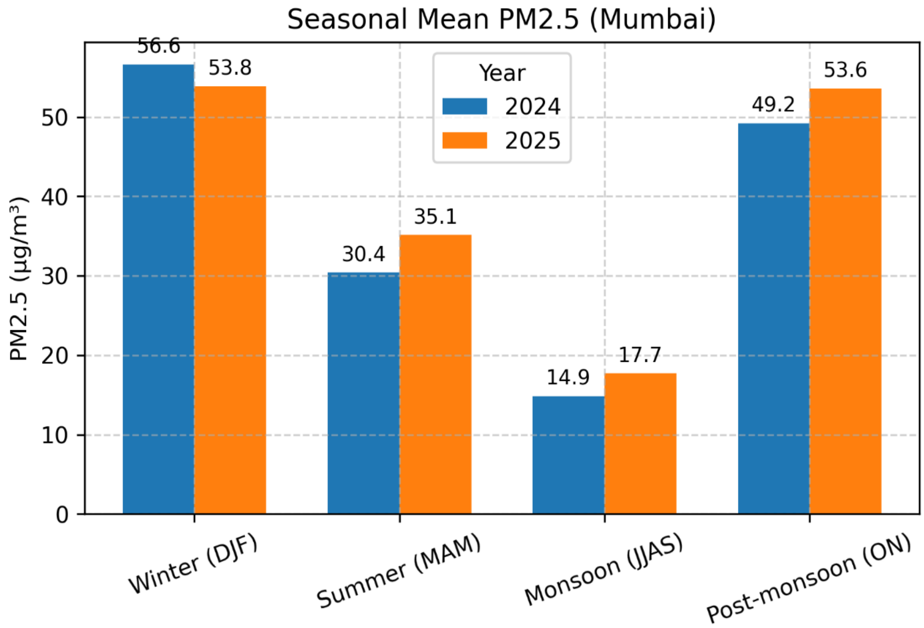

Figure-15: Seasonal Bar plot of PM2.5 for Mumbai city.

The monthly average PM2.5 concentrations further highlight these trends. In 2024, the highest monthly mean was observed in December (66.5 µg/m³), followed by November (65.0 µg/m³) and February (52.2 µg/m³), while the cleanest period occurred during the monsoon, with July recording the lowest mean of 12.1 µg/m³. In 2025, several months showed higher pollution compared to 2024, particularly March (48.7 µg/m³) and October (46.0 µg/m³). Winter months remained polluted, with January (54.9 µg/m³) and February (54.3 µg/m³) showing elevated levels, though December declined to 52.4 µg/m³ compared to the previous year. Overall, the mean values indicate that Mumbai experienced slightly higher PM2.5 levels in 2025 during summer, monsoon, and post-monsoon months, while winter pollution showed minor improvement, underscoring the city's persistent seasonal air quality challenges.

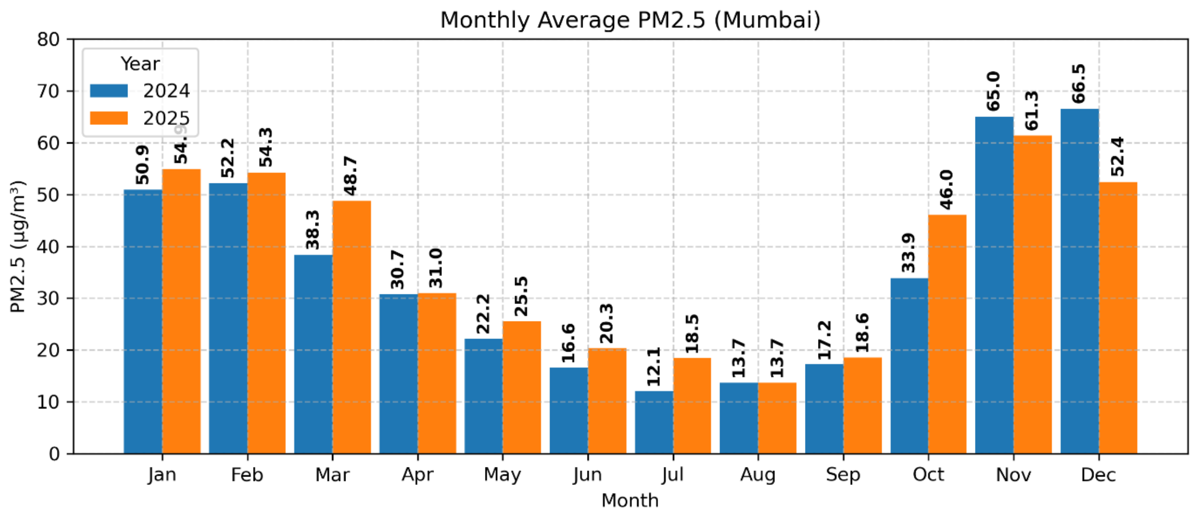

Figure-16: Monthly Bar plot of PM2.5 for Mumbai city.

For Patna:

The seasonal mean PM2.5 concentrations in Patna indicate persistently high pollution levels, particularly during winter and post-monsoon seasons, although some improvement is evident in 2025. In 2024, winter (DJF) recorded an extremely high seasonal mean of 113.7 µg/m³, followed by post-monsoon (ON) at 91.0 µg/m³, reflecting severe air quality conditions. Summer (MAM) also remained heavily polluted with a mean of 81.9 µg/m³, while the lowest seasonal mean occurred during the monsoon (JJAS) at 39.5 µg/m³. In 2025, seasonal means declined across all seasons, indicating overall improvement. Winter PM2.5 decreased to 91.1 µg/m³, summer dropped sharply to 57.0 µg/m³, monsoon fell to 29.7 µg/m³, and post-monsoon reduced to 59.6 µg/m³. Despite these reductions, seasonal mean values in Patna remained well above safe air quality thresholds.

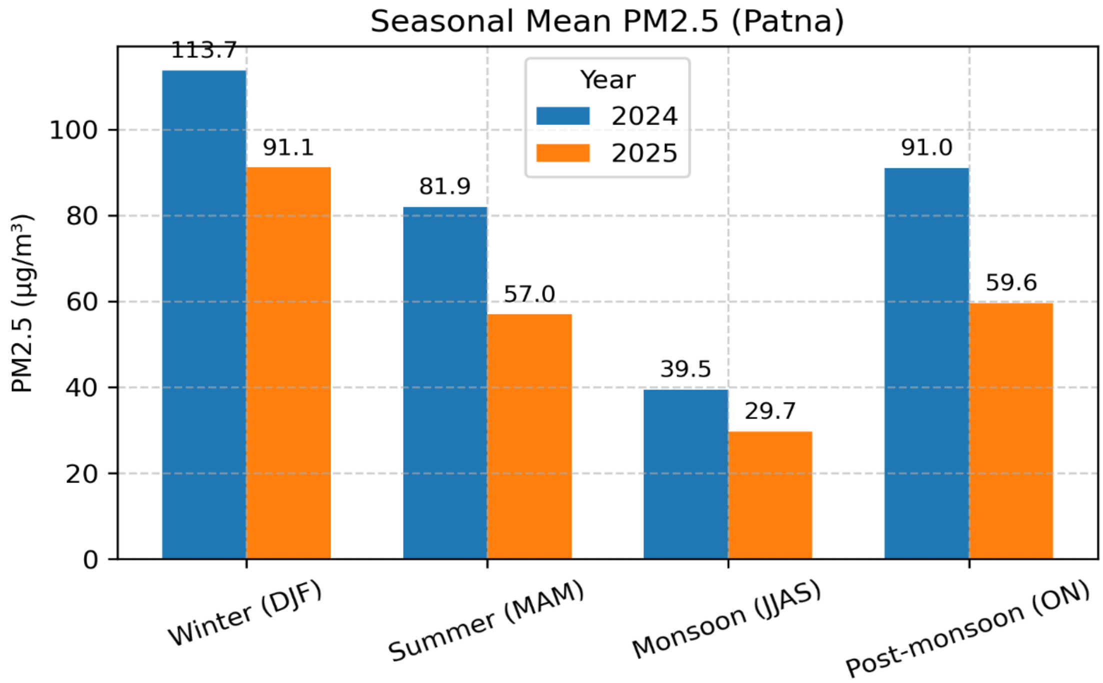

Figure-17: Seasonal Bar plot of PM2.5 for Patna city.

The monthly average PM2.5 concentrations reveal the intensity and persistence of pollution throughout the year. In 2024, the highest monthly mean occurred in January (136.0 µg/m³), followed closely by November (115.1 µg/m³) and December (113.5 µg/m³), underscoring extreme winter pollution episodes. Even during summer months, PM2.5 levels frequently exceeded 70-95 µg/m³, with April averaging 96.2 µg/m³. In 2025, substantial improvements were observed in most months; however, pollution remained severe in winter, with January at 114.1 µg/m³ and December at 73.8 µg/m³. The cleanest period in both years occurred during the monsoon, particularly August 2025 (22.3 µg/m³). Overall, the mean monthly trends suggest that Patna experienced meaningful air quality improvement in 2025, though it continues to face critical pollution levels, especially during winter and post-monsoon months.

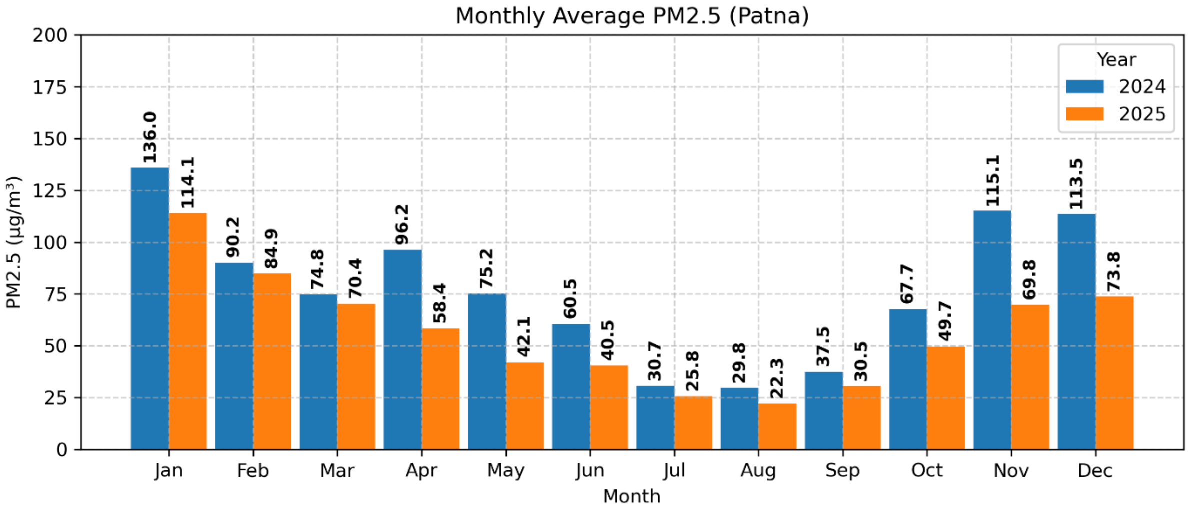

Figure-18: Monthly Bar plot of PM2.5 for Patna city.

3.3 Annual mean for each city

The annual mean PM2.5 concentrations across the six cities show contrasting trends between 2024 and 2025, highlighting both improvements and deteriorations in air quality. Delhi recorded the highest annual mean among all cities, decreasing from 101.2 µg/m³ in 2024 to 94.5 µg/m³ in 2025, representing a reduction of about 6.6%, indicating a modest improvement though levels remain extremely high. Patna also showed a substantial improvement, with the annual mean declining from 77.2 µg/m³ to 56.7 µg/m³, a significant reduction of approximately 26.6%, the largest improvement among the cities. Bengaluru experienced a decline from 29.0 µg/m³ in 2024 to 25.9 µg/m³ in 2025, corresponding to a reduction of about 10.7%, reflecting relatively cleaner air and further improvement. In contrast, Chennai's annual mean increased from 27.5 µg/m³ to 30.5 µg/m³, marking an increase of roughly 10.9%, while Mumbai's mean rose from 34.9 µg/m³ to 37.0 µg/m³, an increase of about 6.0%, indicating worsening air quality in these coastal cities.

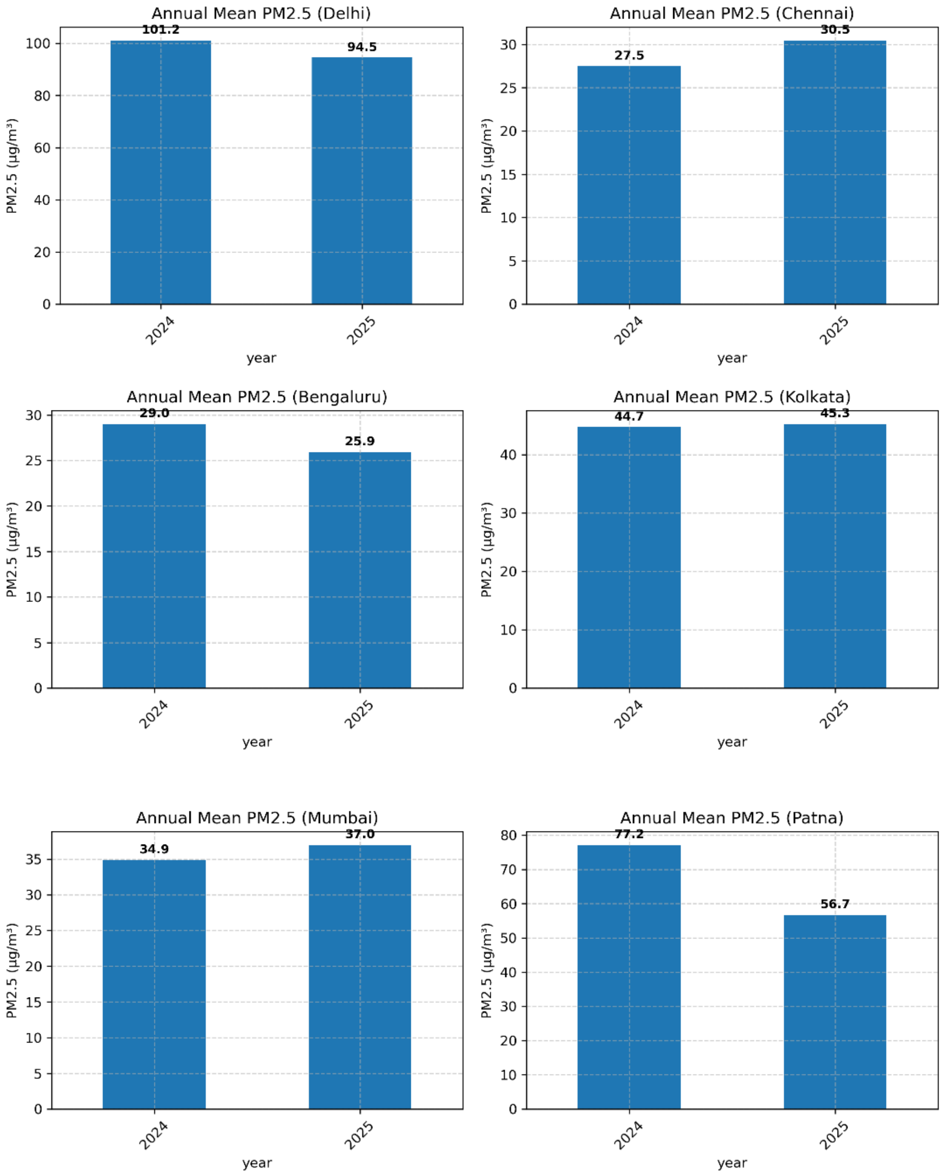

Figure -19: Bar plot of annual PM2.5 for each city.

In comparative terms, Patna and Delhi showed clear reductions in annual PM2.5, with Patna exhibiting the most pronounced improvement in percentage terms, suggesting effective mitigation or favourable meteorological influences in 2025. Bengaluru maintained the lowest annual mean levels among all cities in both years and continued to improve, reinforcing its relatively better air quality status. Conversely, Chennai and Mumbai experienced increases, with Chennai showing the highest percentage rise, pointing to emerging air quality concerns despite its lower absolute PM2.5 levels compared to northern cities. Overall, while northern cities showed notable reductions in annual mean PM2.5, air pollution remains severe there, and the rising trends in Chennai and Mumbai highlight the need for strengthened air quality management across all regions, not only traditionally polluted hotspots.

3.4 PM2.5 Compliance for each city

3.4.1 Intra-city comparison (within each city: 2024 vs 2025)

Delhi shows the worst compliance profile among all cities. In 2024, compliance was 0% in January, November, and December, extremely low in February (3.4%), and only moderate during summer (March 16.1%, April 23.3%, May 9.7%). Monsoon months were the only clean period, peaking at 100% in August and 96.8% in July. In 2025, monsoon performance improved further (July-August 100%, September 96.7%), and summer showed some gains (March 38.7%, May 51.6%). However, winter remained completely non-compliant (0% in Jan, Nov, Dec), indicating structural seasonal failure despite marginal summer improvements.

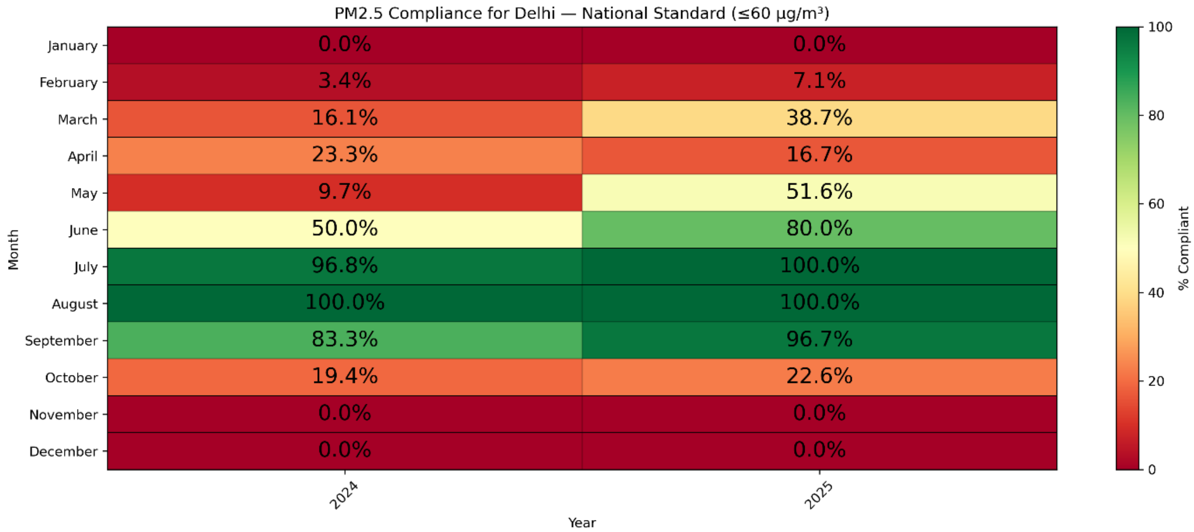

Figure -20: % of compliance for Delhi.

Chennai maintained very high compliance across both years. In 2024, compliance was 100% from February to September, slightly lower in January (90.3%), October (90.3%), and November (90.0%). In 2025, most months still achieved 100%, but some winter and post-monsoon deterioration occurred: January dropped to 83.9%, November to 83.3%, and December sharply declined to 64.5%. This indicates mild winter degradation but overall strong regulatory compliance.

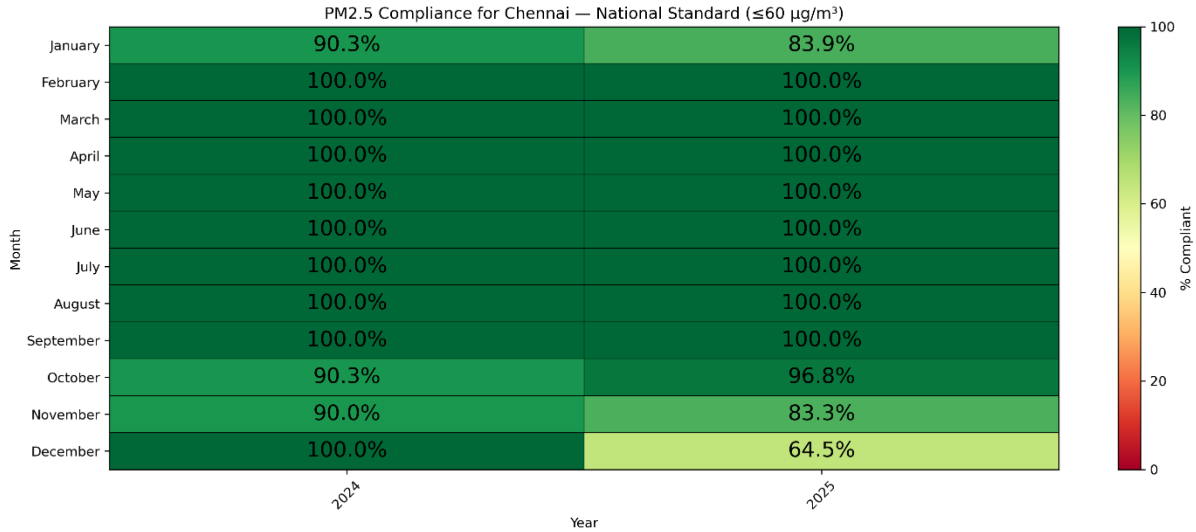

Figure -21: % of compliance for Chennai.

Bengaluru demonstrated the most consistent compliance. In 2024, nearly all months recorded 100% compliance, with only minor reductions in February (93.1%), October (90.3%), and November (96.7%). In 2025, compliance remained 100% from January to October, but declined slightly in November (93.3%) and more noticeably in December (71.0%). Despite this, Bengaluru remained the best-performing city overall.

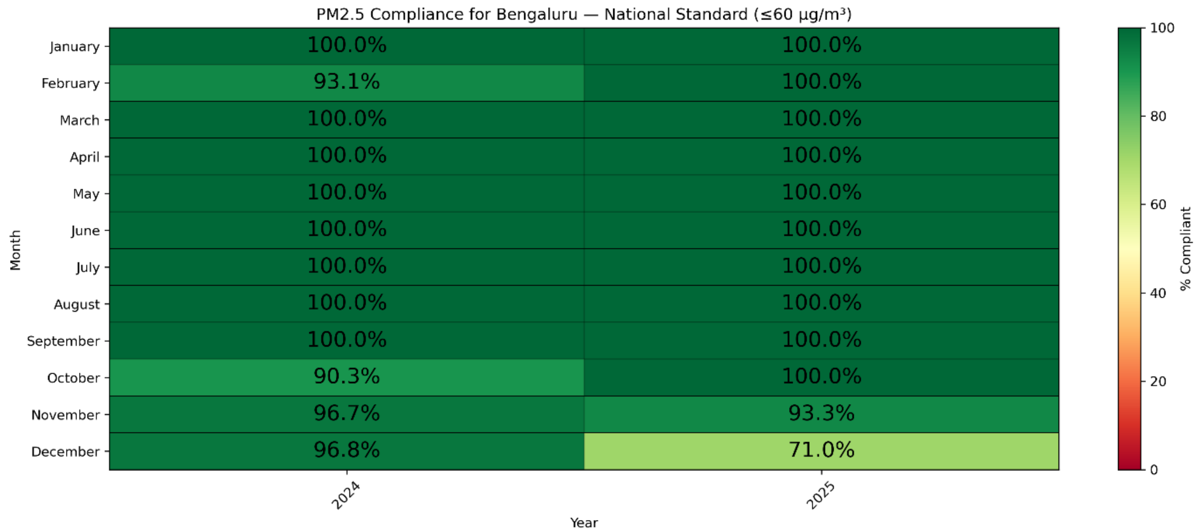

Figure -22: % of compliance for Bengaluru.

Kolkata showed strong seasonal contrasts. In 2024, winter compliance was very poor (January 3.2%, February 34.5%, December 16.1%), while summer and monsoon were excellent (May-September 100%, April 93.3%). In 2025, early-year compliance improved (January 12.9%, February 53.6%, March 87.1%), but post-monsoon and winter worsened, with November falling to 13.3% and December to 0%, showing a shift of pollution severity toward late 2025.

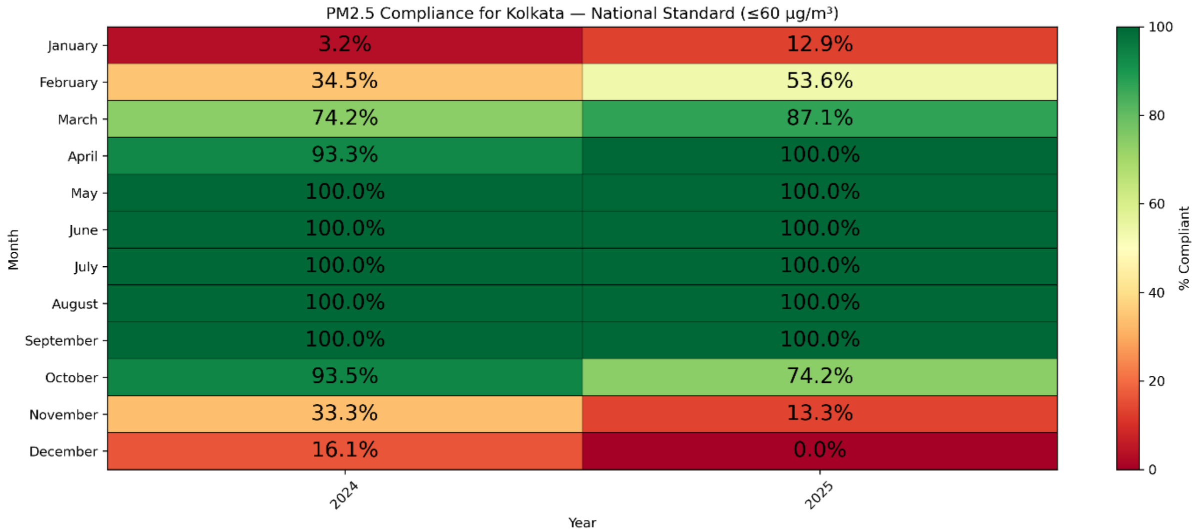

Figure -23: % of compliance for Kolkata.

Mumbai displayed moderate but uneven compliance. In 2024, compliance was high during April-September (100%), but weaker in winter (January 83.9%, February 75.9%) and sharply lower in November (26.7%) and December (35.5%). In 2025, summer and monsoon again achieved 100%, winter slightly weakened (January 74.2%, February 71.4%), but December improved strongly to 74.2%, indicating better late-winter conditions compared to 2024.

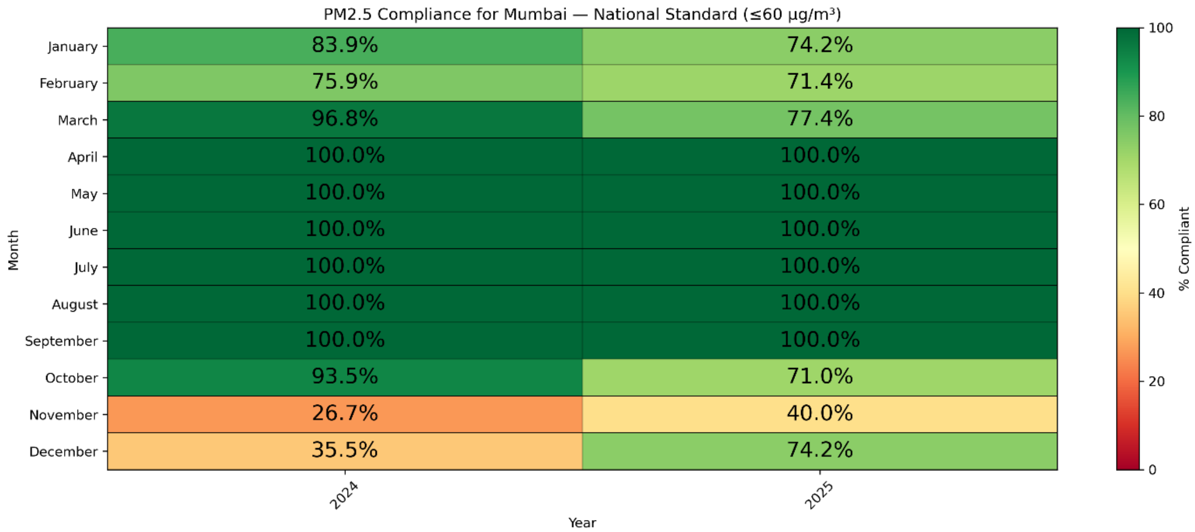

Figure -24: % of compliance for Mumbai.

Patna remained severely non-compliant, though 2025 showed clear improvement. In 2024, compliance was 0% in January, April, November, and December, very low in February (10.3%), and moderate only during monsoon (July-August 100%, September 96.7%). In 2025, compliance improved substantially in summer and monsoon (May 93.5%, June 90%, July-September 100%), and October rose to 77.4%, but winter remained critical, with January still at 0% and December only 19.4%.

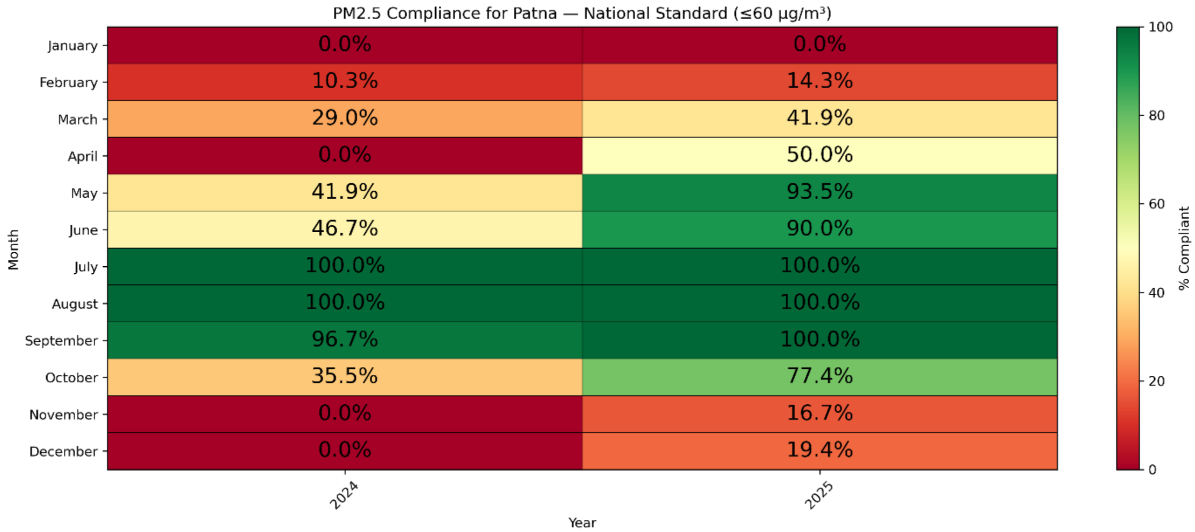

Figure -25: % of compliance for Patna.

3.4.2 Inter-city comparison (between cities)

Across both years, Bengaluru ranked highest, showing near-perfect compliance (>95%) for most months, followed closely by Chennai, which remained compliant in over 90% of months, despite some winter decline in 2025. Mumbai occupied a middle position, with strong summer-monsoon compliance but recurring winter and post-monsoon failures, though December improved in 2025. Kolkata showed strong monsoon performance but extreme winter volatility, shifting from poor early-year compliance in 2024 to poor late-year compliance in 2025. Delhi and Patna consistently ranked lowest, with Delhi showing near-total winter non-compliance (0%) in both years, and Patna improving in summer–monsoon 2025 but still failing badly in winter.

In summary, southern cities (Bengaluru, Chennai) demonstrate structural air-quality resilience, western Mumbai shows seasonal vulnerability, eastern Kolkata shows shifting seasonal risk, while northern cities (Delhi and Patna) remain chronically non-compliant, especially in winter, underscoring deep-rooted pollution challenges that seasonal improvements alone cannot offset.

3.5 Impact of metrology on PM2.5 for each city

We applied meteorology-based clustering to understand how atmospheric conditions control daily PM2.5 variability across the six cities (Delhi, Chennai, Bengaluru, Kolkata, Mumbai, and Patna). For each city, a multivariate dataset consisting of wind speed (WS), wind direction (WD), temperature (Temp), and relative humidity (RH) was first standardized to remove scale effects. K-means clustering was then applied independently for each city to group days with similar meteorological regimes. The optimal number of clusters (k) was selected using the silhouette score, ensuring that each city's clustering maximized intra-cluster similarity and inter-cluster separation. This resulted in four distinct meteorological clusters for all cities, representing recurring regimes such as stagnant winter conditions (low WS, low temperature), transitional seasons (moderate WS and temperature), monsoon regimes (high RH and stronger winds), and post-monsoon/variable conditions.

The clustered PM2.5 time-series plots clearly show inter-cluster contrasts and intra-cluster consistency in pollution behaviour. In Delhi and Patna, clusters associated with low wind speed and cooler temperatures dominate winter months and correspond to very high PM2.5 levels, often exceeding 150-300 µg/m³, highlighting the role of stagnation and inversion conditions. In contrast, clusters linked to monsoon conditions (high RH, higher WS) show sharp PM2.5 reductions, frequently below 50 µg/m³. Kolkata and Mumbai display intermediate behaviour: winter and post-monsoon clusters show elevated PM2.5 (60–120 µg/m³), while monsoon clusters consistently suppress concentrations. Chennai and Bengaluru exhibit the least extreme contrasts, with clusters reflecting more stable meteorology and PM2.5 mostly remaining below 60 µg/m³, except during specific post-monsoon or winter regimes. Overall, the clustering demonstrates that meteorology-driven regimes systematically control PM2.5 variability, and the silhouette-optimized K-means approach robustly captures these city-specific pollution–weather relationships.

For Delhi:

The results show strong meteorological control on PM2.5 variability. Cluster 0 is the most dominant and polluted regime, accounting for 290 days, with the highest mean PM2.5 concentration of 115.44 µg/m³ and a median of 93.20 µg/m³. This cluster is characterized by very low wind speed (0.91 m/s), moderately high RH (66.8%), low temperature (21.8 °C), and winds primarily from the south–southwest (≈199°), conditions that strongly favour pollutant accumulation and stagnation, typical of Delhi's winter and post-monsoon periods. Cluster 1, occurring on 236 days, also exhibits high pollution with a mean PM2.5 of 97.09 µg/m³, but a much lower median of 44.68 µg/m³, indicating episodic pollution events. This regime is associated with high humidity (76.4%), low temperature (22.0 °C), and low wind speed (0.99 m/s), which likely enhances secondary aerosol formation, leading to sharp pollution peaks rather than persistent buildup. In contrast, Cluster 2 represents a comparatively cleaner regime with a mean PM2.5 of 76.30 µg/m³, occurring on 92 days, and is defined by higher wind speed (1.25 m/s), low RH (40.0%), and high temperature (30.0 °C), conditions favourable for atmospheric mixing and dispersion during the pre-monsoon season. Cluster 3 shows the lowest mean PM2.5 concentration (71.94 µg/m³) across 113 days, characterized by the highest wind speed (1.28 m/s), moderate RH (50.2%), and warm temperatures (29.0 °C), representing well-ventilated transitional or monsoon-influenced conditions. Overall, the clustering clearly demonstrates that Delhi's highest PM2.5 levels are strongly associated with low wind speed, lower temperatures, and elevated humidity, while cleaner conditions coincide with enhanced ventilation and warmer atmospheric regimes.

Table-1: Metrology cluster wise variations for Delhi

Met. Cluster	Mean PM2.5 (µg/m³)	Median PM2.5 (µg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 0	115.44	93.20	290	0.91	66.77	21.79	198.76	Highly polluted, stagnant winter/post-monsoon regime
Cluster 1	97.09	44.68	236	0.99	76.35	22.02	168.82	Humid, low-wind regime with episodic pollution peaks
Cluster 2	76.30	70.75	92	1.25	39.99	29.99	193.86	Hot, dry, well-ventilated summer regime
Cluster 3	71.94	70.61	113	1.28	50.22	28.96	165.20	Warm, moderately ventilated transition/monsoon regime

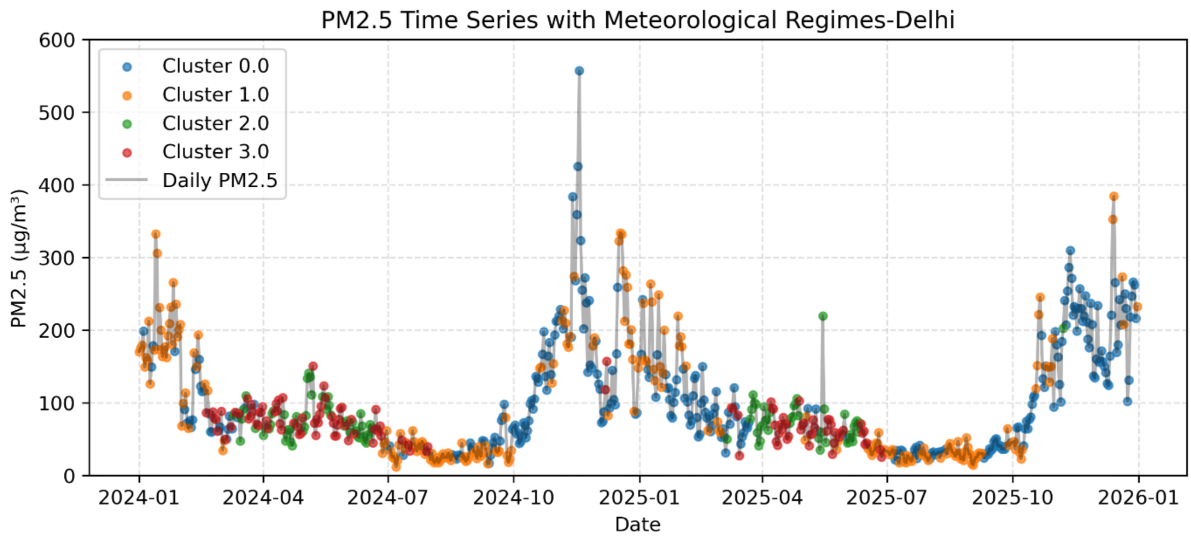

Figure -26: Time series plot of PM2.5 with metrological cluster for Delhi.

Key points (Delhi)

- Four meteorological regimes were objectively identified using silhouette-optimized K-means clustering.

- Cluster 0 and Cluster 1 together account for ~72% of days, explaining Delhi's persistent air pollution problem.
- Lowest wind speed (<1 m/s) corresponds to the highest PM2.5 concentrations (>115 µg/m³).
- High humidity (>65%) plays a key role in secondary aerosol formation, especially in Cluster 1.
- Higher wind speeds (>1.2 m/s) and higher temperatures (~30 °C) in Clusters 2 and 3 reduce PM2.5 by ~35-40% compared to the most polluted regime.
- The results confirm that meteorology is a dominant driver of PM2.5 variability in Delhi, amplifying pollution during winter and suppressing it during summer and monsoon periods.

For Bengaluru:

The results indicate that Bengaluru experiences moderate PM2.5 levels with comparatively weaker meteorological contrasts than northern Indian cities. Cluster 0 represents the most polluted regime, accounting for 223 days, with a mean PM2.5 concentration of 36.47 µg/m³ and a median of 35.57 µg/m³. This cluster is characterized by moderate wind speed (0.78 m/s), high relative humidity (64.8%), and higher temperature (26.9 °C), suggesting limited dispersion under humid and relatively warm conditions. Cluster 1, occurring on 85 days, shows a substantially lower pollution load with a mean PM2.5 of 23.47 µg/m³ and median of 19.48 µg/m³, associated with slightly lower temperature (24.5 °C) and winds predominantly from the west-southwest (≈253°), favouring better ventilation. Cluster 2, the most frequent regime with 238 days, exhibits moderate PM2.5 levels (mean = 24.76 µg/m³) and is characterized by the lowest wind speed (0.68 m/s), lower humidity (56.5%), and moderate temperature (24.6 °C), reflecting relatively stable but not severely polluted conditions. Cluster 3, spanning 184 days, records the lowest mean PM2.5 concentration (21.78 µg/m³) with a median of 16.94 µg/m³, associated with moderate wind speed (0.73 m/s), moderate humidity (62.4%), and temperatures around 24.5 °C, representing the cleanest and most ventilated meteorological regime in Bengaluru. Overall, the clustering highlights that Bengaluru's PM2.5 variability is less extreme and is primarily controlled by subtle changes in wind speed and humidity rather than strong seasonal stagnation.

Table-2: Metrology cluster wise variations for Bengaluru

Met. Cluster	Mean PM2.5 (µg/m³)	Median PM2.5 (µg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 0	36.47	35.57	223	0.78	64.77	26.92	142.78	Most polluted, humid and weakly ventilated regime

Met. Cluster	Mean PM2.5 (µg/m³)	Median PM2.5 (µg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 1	23.47	19.48	85	0.74	62.26	24.53	253.13	Cleaner regime with favourable wind direction
Cluster 2	24.76	21.39	238	0.68	56.51	24.55	170.09	Stable, moderately clean dominant regime
Cluster 3	21.78	16.94	184	0.73	62.36	24.45	200.30	Cleanest, well-ventilated regime

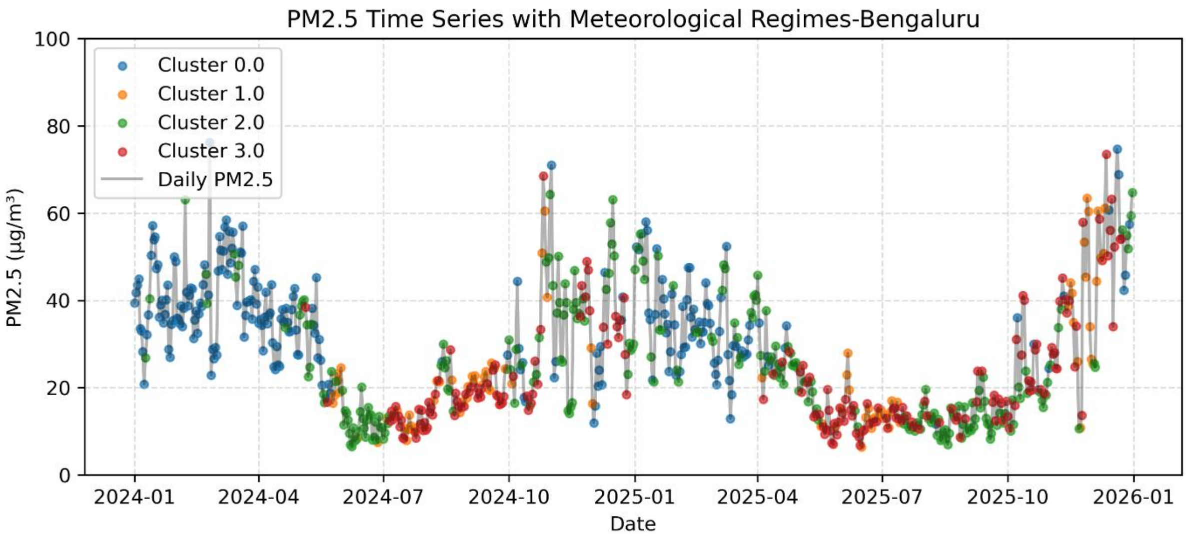

Figure -27: Time series plot of PM2.5 with metrological cluster for Bengaluru.

Key points (Bengaluru)

- Four meteorological regimes were identified using silhouette-optimized K-means clustering.
- Cluster 0 represents the highest PM2.5 regime, though concentrations remain moderate (<40 µg/m³).
- PM2.5 variability is narrower compared to northern cities, reflecting Bengaluru's favourable dispersion conditions.
- Lower wind speed and higher humidity contribute to relatively higher PM2.5 in Cluster 0.

- Cluster 3 shows the cleanest air quality, with mean PM2.5 nearly 40% lower than the most polluted regime.
- Meteorology modulates pollution in Bengaluru mainly through ventilation efficiency rather than temperature extremes.

For Chennai:

The clustering results indicate that Chennai experiences relatively low to moderate PM2.5 concentrations, strongly influenced by high wind speeds and persistent marine humidity. Cluster 0 is the dominant regime, accounting for 370 days, with a mean PM2.5 concentration of 28.82 µg/m³ and a median of 23.43 µg/m³. This cluster is characterized by moderately high wind speed (3.27 m/s), high relative humidity (75.1%), and warm temperatures (28.8 °C), reflecting typical coastal conditions that support effective dispersion. Cluster 1, occurring on 128 days, shows a higher pollution load with a mean PM2.5 of 33.49 µg/m³ and median 30.40 µg/m³, associated with reduced wind speed (2.68 m/s) and very high humidity (76.6%), suggesting episodic accumulation under weaker ventilation. Cluster 2, spanning 216 days, represents the cleanest and most ventilated regime, with a mean PM2.5 concentration of 26.19 µg/m³, supported by the highest wind speed (3.74 m/s) and the highest temperature (29.1 °C), which enhance boundary-layer mixing. Cluster 3, though rare with only 17 days, exhibits the highest mean PM2.5 concentration (34.53 µg/m³) and median 34.82 µg/m³, despite the strongest wind speed (4.34 m/s), indicating short-lived pollution episodes likely driven by local emissions or directional transport effects rather than meteorological stagnation. Overall, the clustering highlights that Chennai's air quality remains relatively stable, with wind speed acting as the primary controlling factor, while humidity modulates short-term PM2.5 variability.

Table-3: Metrology cluster wise variations for Chennai

Met. Cluster	**Mean PM2.5 (µg/m³)**	**Median PM2.5 (µg/m³)**	**No. of Days**	**Wind Speed (m/s)**	**Relative Humidity (%)**	**Temperature (°C)**	**Wind Direction (°)**	**Regime Interpretation**
Cluster 0	28.82	23.43	370	3.27	75.09	28.78	169.62	Dominant coastal regime with good ventilation
Cluster 1	33.49	30.40	128	2.68	76.56	28.30	142.43	Humid, weakly ventilated regime with higher PM2.5
Cluster 2	26.19	23.33	216	3.74	74.20	29.12	191.73	Cleanest, well-mixed regime

Met. Cluster	Mean PM2.5 (μg/m³)	Median PM2.5 (μg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 3	34.53	34.82	17	4.34	75.34	27.76	103.09	Rare episodic pollution regime

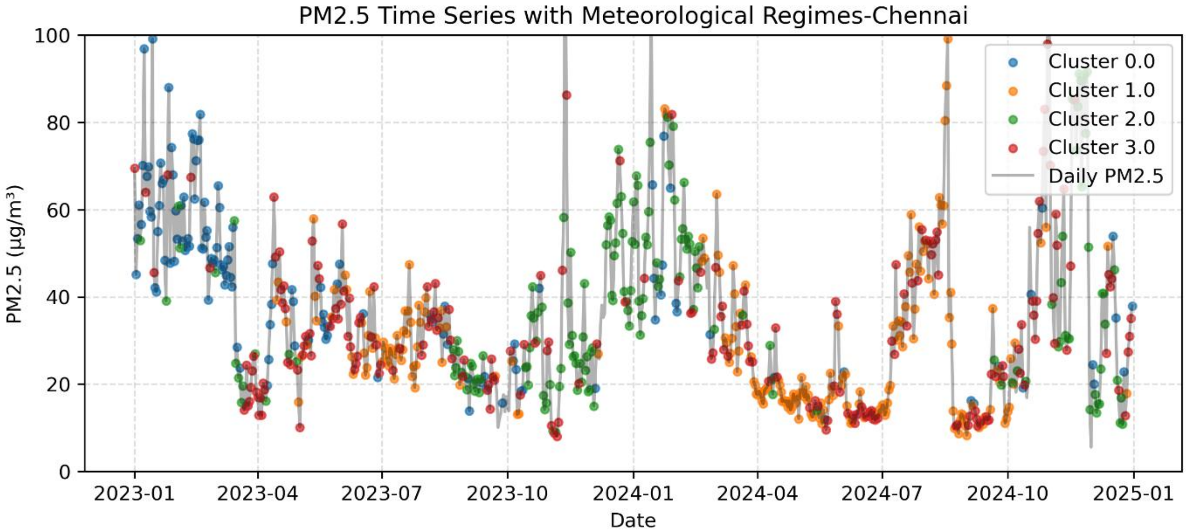

Figure -28: Time series plot of PM2.5 with metrological cluster for Chennai.

Key points (Chennai)

- Four meteorological regimes were identified using silhouette-optimized K-means clustering.
- Overall PM2.5 levels are moderate, remaining mostly below 35 μg/m³ across regimes.
- High wind speeds (>3 m/s) dominate Chennai's climate and promote effective pollutant dispersion.
- Cluster 1 and Cluster 3 show relatively higher PM2.5 under reduced ventilation or specific wind directions.
- Cluster 3, though rare, represents episodic pollution events rather than persistent conditions.
- The results emphasize the protective role of coastal meteorology in regulating PM2.5 over Chennai.

For Kolkata:

The results show that Kolkata experiences pronounced contrasts between polluted and cleaner regimes, strongly modulated by low wind speeds and high humidity. Cluster 0 represents one of the dominant polluted regimes, accounting for 270 days, with a mean PM2.5 concentration of 53.37 μg/m³ and a median of 42.57 μg/m³. This cluster is characterized by low wind speed

(0.79 m/s), high relative humidity (75.4%), and moderate temperature (25.6 °C), conditions that favour pollutant accumulation. Cluster 2, covering 226 days, exhibits similarly high pollution levels with a mean PM2.5 of 53.74 µg/m³ and median 47.19 µg/m³, associated with very weak ventilation (0.81 m/s) and a slightly warmer environment (27.3 °C), indicating stagnation-driven pollution episodes. In contrast, Cluster 1, occurring on 82 days, represents the cleanest regime, with a mean PM2.5 concentration of only 23.59 µg/m³ and median 16.87 µg/m³, supported by the highest wind speed (1.10 m/s) and very high humidity (85.9%), suggesting efficient dispersion despite moist conditions. Cluster 3, spanning 153 days, reflects a moderately polluted regime with mean PM2.5 of 28.83 µg/m³, characterized by moderate wind speed (0.91 m/s) and high humidity (82.4%). Overall, the clustering highlights that Kolkata's PM2.5 variability is primarily controlled by ventilation strength, with low wind speed regimes consistently associated with elevated pollution, especially during humid conditions.

Table-4: Metrology cluster wise variations for Kolkata

Met. Cluster	**Mean PM2.5 (µg/m³)**	**Median PM2.5 (µg/m³)**	**No. of Days**	**Wind Speed (m/s)**	**Relative Humidity (%)**	**Temperature (°C)**	**Wind Direction (°)**	**Regime Interpretation**
Cluster 0	53.37	42.57	270	0.79	75.44	25.56	190.70	Polluted stagnation regime
Cluster 1	23.59	16.87	82	1.10	85.85	25.32	128.89	Cleanest, well-ventilated regime
Cluster 2	53.74	47.19	226	0.81	70.58	27.28	208.01	Warm, low wind polluted regime
Cluster 3	28.83	21.81	153	0.91	82.41	26.34	157.24	Moderately polluted humid regime

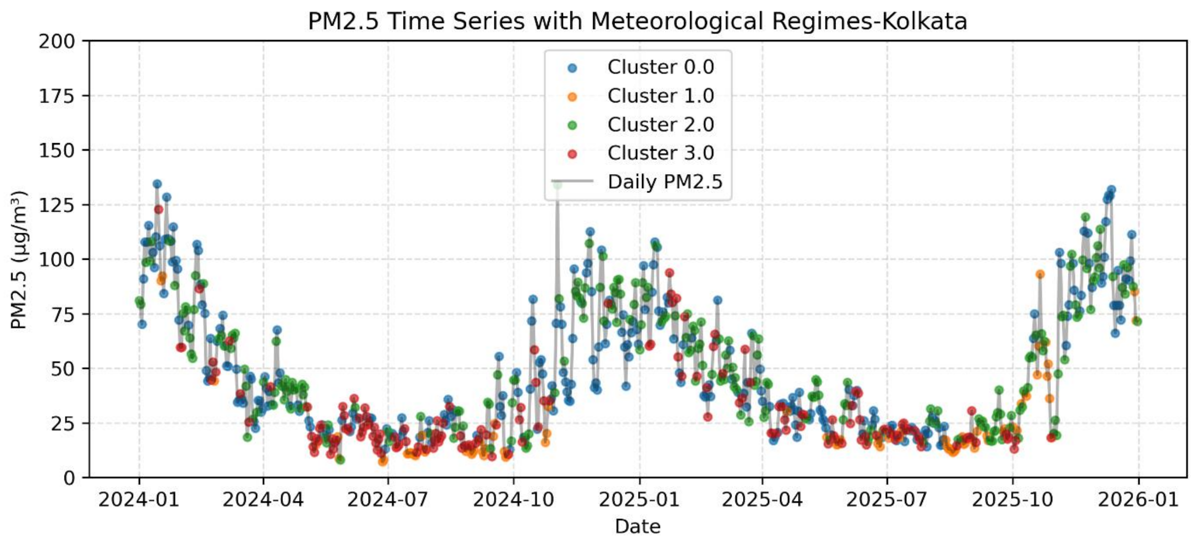

Figure -29: Time series plot of PM2.5 with metrological cluster for Kolkata.

Key points (Kolkata)

- Four meteorological regimes were identified using silhouette-optimized K-means clustering.
- Clusters 0 and 2 are the most polluted regimes, both with mean PM2.5 > 53 µg/m³.
- Low wind speeds (<1 m/s) are the dominant driver of high PM2.5 accumulation.
- Cluster 1 represents the cleanest conditions, associated with relatively stronger winds.
- High relative humidity (>70%) persists across all regimes, amplifying stagnation effects.
- Kolkata shows long-lasting polluted regimes, unlike coastal cities where clean regimes dominate.

For Mumbai:

The clustering results show that Mumbai's PM2.5 variability is strongly influenced by wind-driven dispersion, consistent with its coastal setting. Cluster 1 is the most dominant and polluted regime, encompassing 263 days, with a mean PM2.5 concentration of 43.60 µg/m³ and a median of 44.47 µg/m³. This cluster is associated with moderate wind speeds (5.56 m/s), lower relative humidity (66.6%), and high temperatures (~32.9°C), suggesting enhanced local emissions and limited vertical mixing despite moderate winds. Cluster 2, covering 207 days, represents a moderately polluted regime with a mean PM2.5 of 35.84 µg/m³, supported by stronger wind speeds (8.11 m/s) and higher humidity (74.0%), indicating partial dispersion. Cluster 0, occurring on 122 days, shows similar pollution levels (mean PM2.5 = 34.66 µg/m³) but under very high wind speeds (8.18 m/s) and elevated humidity (73.9%), reflecting efficient ventilation that prevents extreme accumulation. In contrast, Cluster 3, spanning 128 days, is the cleanest regime, with a mean PM2.5 concentration of only 22.71 µg/m³ and median 18.52 µg/m³, associated with very low wind speeds (2.59 m/s) and high humidity (74.6%), suggesting periods dominated by marine air inflow rather than continental pollution. Overall, the clustering highlights that Mumbai's PM2.5 levels remain moderate, with coastal winds acting as the primary control on air quality, and pollution peaks occurring when wind direction and emission intensity align unfavourably.

Table-5: Metrology cluster wise variations for Mumbai

Met. Cluster	Mean PM2.5 (µg/m³)	Median PM2.5 (µg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 0	34.66	23.17	122	8.18	73.91	32.91	112.29	Highly ventilated coastal regime
Cluster 1	43.60	44.47	263	5.56	66.62	32.88	155.82	Dominant polluted regime
Cluster 2	35.84	29.33	207	8.11	74.05	32.85	188.93	Moderately polluted, windy regime
Cluster 3	22.71	18.52	128	2.59	74.59	-	55.75	Clean marine-influenced regime

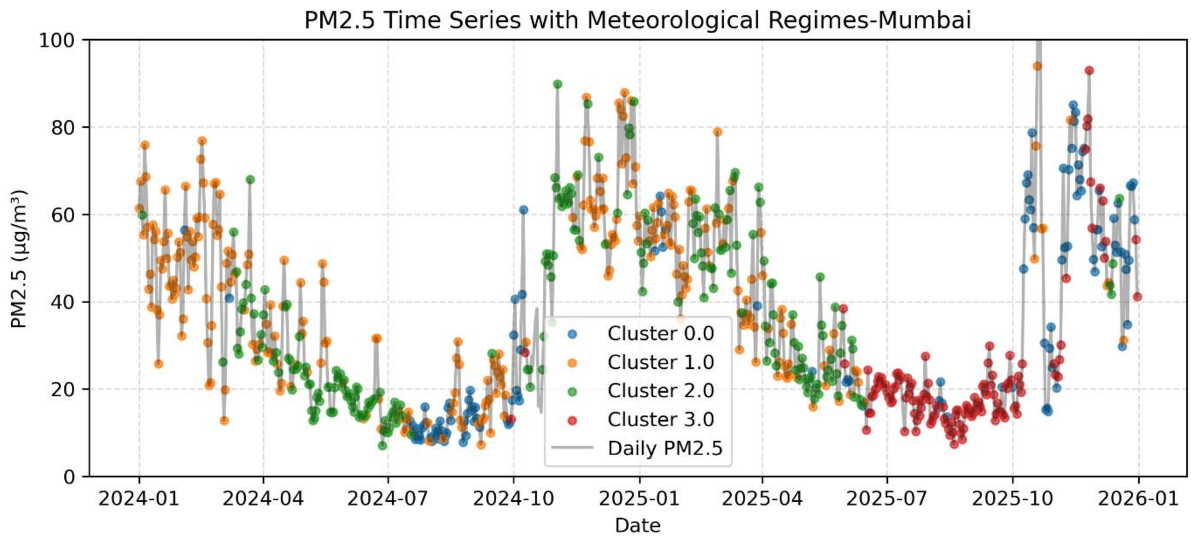

Figure -30: Time series plot of PM2.5 with metrological cluster for Mumbai.

Key points (Mumbai)

- Four meteorological regimes were identified using silhouette-optimized K-means clustering.

- Cluster 1 is the most polluted and frequent regime (mean PM2.5 ≈ 43.6 µg/m³).
- High wind speeds (>8 m/s) generally support pollutant dispersion and limit extreme PM2.5 buildup.
- Cluster 3 represents the cleanest conditions, dominated by marine-influenced airflow.

For Patna:

The results reveal that Patna experiences persistently high PM2.5 concentrations, primarily driven by very weak ventilation and high humidity, typical of the Indo-Gangetic Plain. Cluster 0 represents the most polluted and dominant regime, accounting for 241 days, with a mean PM2.5 concentration of 84.96 µg/m³ and a median of 81.61 µg/m³. This cluster is characterized by the lowest wind speed (0.51 m/s), very high relative humidity (80.2%), and moderate temperature (28.2 °C), conditions that strongly favour pollutant accumulation. Cluster 2, occurring on 129 days, also exhibits very high pollution levels with a mean PM2.5 of 78.00 µg/m³ and median 73.95 µg/m³, associated with low wind speed (0.71 m/s) and much lower humidity (46.6%), suggesting dry stagnation episodes with limited dispersion. Cluster 3, spanning 152 days, reflects a moderately polluted regime with mean PM2.5 of 68.38 µg/m³, characterized by weak winds (0.54 m/s) and high humidity (74.9%), indicating moisture-enhanced aerosol persistence. In contrast, Cluster 1, covering 209 days, represents the cleanest regime for Patna, with a mean PM2.5 concentration of 38.37 µg/m³ and median 33.14 µg/m³, supported by the highest wind speed (0.93 m/s) and relatively lower humidity (74.1%). Overall, the clustering highlights that Patna's air quality is dominated by stagnation-driven regimes, with wind speed emerging as the most critical controlling factor, and even the cleanest regime remaining above national standards for extended periods.

Table-5: Metrology cluster wise variations for Patna

Met. Cluster	**Mean PM2.5 (µg/m³)**	**Median PM2.5 (µg/m³)**	**No. of Days**	**Wind Speed (m/s)**	**Relative Humidity (%)**	**Temperature (°C)**	**Wind Direction (°)**	**Regime Interpretation**
Cluster 0	84.96	81.61	241	0.51	80.23	28.15	216.06	Highly polluted stagnation regime
Cluster 1	38.37	33.14	209	0.93	74.07	27.43	106.76	Relatively cleaner, ventilated regime
Cluster 2	78.00	73.95	129	0.71	46.57	27.30	229.36	Dry, low-wind polluted regime

Met. Cluster	Mean PM2.5 (µg/m³)	Median PM2.5 (µg/m³)	No. of Days	Wind Speed (m/s)	Relative Humidity (%)	Temperature (°C)	Wind Direction (°)	Regime Interpretation
Cluster 3	68.38	57.05	152	0.54	74.95	27.96	157.32	Humid stagnation regime

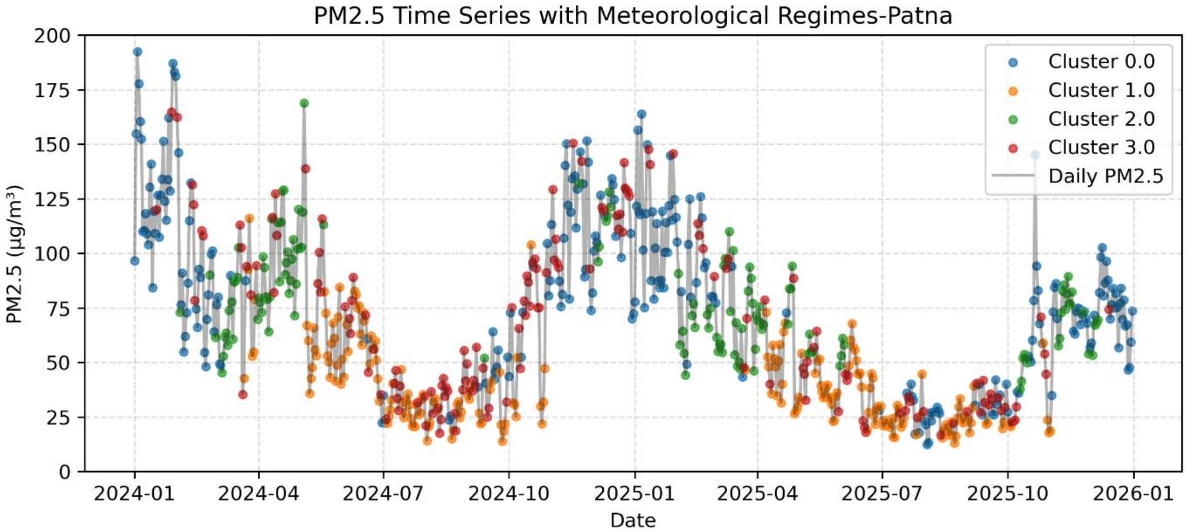

Figure -31: Time series plot of PM2.5 with metrological cluster for Patna.

Key points (Patna)

- Four meteorological regimes were identified using silhouette-optimized K-means clustering.
- Cluster 0 is the most polluted and frequent regime (mean PM2.5 ≈ 85 µg/m³).
- Extremely low wind speeds (<1 m/s) dominate across all regimes, limiting dispersion.
- High humidity (>70%) amplifies aerosol persistence and secondary particle formation.
- Even the cleanest regime (Cluster 1) shows moderate PM2.5 levels, indicating structural pollution.
- Patna exhibits the strongest stagnation-driven pollution among the analysed cities.

3.6 Conclusion

This multi-city analysis demonstrates that PM2.5 pollution in Indian urban environments is fundamentally governed by the interaction between emissions and meteorology, with atmospheric stagnation emerging as the dominant amplifier of pollution severity. Despite measurable reductions in annual mean PM2.5 most notably in Patna (≈27%) and Delhi (≈7%) between 2024 and 2025 wintertime compliance remained critically poor in stagnation-prone cities, with Delhi recording 0% compliance during peak winter months in both years. Meteorology-based clustering shows that more than 70% of days in northern Indo-Gangetic

Plain cities fall under low-wind (<1 m/s), high-humidity regimes that sustain PM2.5 concentrations exceeding 90-115 µg/m³, while shifts to ventilated regimes alone reduce concentrations by ~35–40% even without emission changes. In contrast, southern and coastal cities consistently maintain lower PM2.5 levels and high compliance due to favourable dispersion conditions, underscoring that observed inter-city contrasts are strongly climate-modulated rather than emission-only outcomes.

From a policy perspective, these findings indicate that emission-centric and annually averaged evaluation frameworks, as currently emphasized under NCAP, are insufficient to address the dominant winter pollution burden and associated health risks. Effective air quality management under NCAP Phase-III must therefore transition toward season-specific, meteorology-informed control strategies, integrating dynamic action triggers based on ventilation thresholds, winter-weighted compliance metrics, and regional airshed-level coordination. The persistence of exceedances even under the cleanest meteorological regimes in Delhi and Patna further indicates structural pollution that cannot be resolved through episodic interventions alone. Incorporating meteorological regime analysis into regulatory planning and performance assessment is thus essential to distinguish true emission-driven improvements from weather-induced variability and to ensure that future policy outcomes translate into sustained reductions in population exposure and public-health risk.

Key Evidence from the Study

- **Delhi:**
  Annual mean PM2.5 reduced by 6.6% (101.2 to 94.5 µg/m³), yet winter compliance remained 0% in both years.
  ~72% of days fall under low-wind (<1 m/s), high-humidity regimes with mean PM2.5 97-115 µg/m³.
- **Patna:**
  Annual mean PM2.5 reduced by 26.6% (77.2 to 56.7 µg/m³), but January compliance remained 0% in 2025. Dominant regimes show wind speeds as low as 0.5 m/s with mean PM2.5 ~85 µg/m³.
- **Southern cities (Bengaluru, Chennai):**
  Annual means remained <31 µg/m³, with >90-95% monthly compliance, supported by stronger ventilation (winds 3-4 m/s in Chennai).
- **Across all cities:**
  Transition from stagnant to ventilated meteorological regimes reduces PM2.5 by ~35-40%, even without emission changes. Monsoon months show near-100% compliance, masking winter failure when annual averages are used.

3.7. Interpretation and Policy-Relevant Insights

❖ The findings demonstrate that observed changes in PM2.5 concentrations across Indian cities cannot be interpreted solely as outcomes of emission control measures, as meteorological conditions play a dominant and often overriding role in shaping air quality trends. In cities such as Delhi and Patna, modest to substantial reductions in annual mean PM2.5 coexist with persistent zero or near-zero compliance during winter months, indicating that unfavourable meteorological regimes characterized by low wind speeds, high humidity, and atmospheric stagnation continue to trap pollutants despite emission reductions. This highlights that improvements in annual averages may overstate progress in regions where pollution is episodic but severe.

- ❖ The regime-based analysis further shows that a large fraction of high-pollution days occurs under a limited set of meteorological conditions, particularly low-wind regimes with wind speeds below 1 m/s. Under these conditions, PM2.5 concentrations remain elevated even when overall annual levels decline, underscoring that winter pollution persistence is largely meteorology-driven rather than purely emission-driven. Conversely, the sharp reduction in PM2.5 (by ~35-40%) observed during transitions to ventilated regimes demonstrates the strong sensitivity of air quality to atmospheric dispersion, independent of changes in emissions.

- ❖ In southern and coastal cities, consistently high compliance rates are closely linked to favourable ventilation conditions rather than lower emissions alone, suggesting that meteorology provides an inherent advantage in meeting standards. Similarly, near-universal compliance during monsoon months across all cities reflects enhanced dispersion and wet scavenging, which can mask underlying emission challenges when assessments rely on annual or monsoon-weighted averages.

Taken together, these results imply that trend-based evaluations without meteorological adjustment risk misattributing both success and failure in air quality management. For policymakers, this underscores the need to complement long-term emission reduction strategies with season and regime-specific interventions, particularly targeting winter stagnation periods in northern cities. Meteorology-informed metrics are therefore essential for realistic target setting, accurate performance evaluation under NCAP, and the design of effective short-term action plans for extreme pollution episodes.

3.8 Implications for NCAP-III

1. Shift from Annual to Seasonal Performance Metrics

The findings clearly demonstrate that annual mean PM2.5 reductions substantially underestimate winter-time health risk, particularly in stagnation-prone regions. For instance, Delhi recorded a 6.6% reduction in annual mean PM2.5 (101.2 to 94.5 μg/m^3) between 2024 and 2025, and Patna showed an even larger 26.6% reduction (77.2 to 56.7 μg/m^3). However, these improvements did not translate into winter compliance, with Delhi exhibiting 0% compliance in January, November, and December in both years, and Patna remaining non-compliant in January even in 2025. Seasonal analysis shows that winter (DJF) and post-monsoon (ON) PM2.5 concentrations in Delhi routinely exceed 150-170 μg/m^3, while monsoon months remain largely compliant due to meteorological washout. This evidence indicates that annual averaging masks critical seasonal exposure, and NCAP-III must therefore adopt season-specific reduction targets, with explicit performance benchmarks for DJF and ON seasons, particularly across the Indo-Gangetic Plain.

2. Introduce Meteorology-Triggered Action Frameworks

Meteorology-based clustering reveals that pollution extremes are strongly associated with specific atmospheric regimes, rather than emission changes alone. In Delhi, nearly 72% of days fall under two dominant polluted regimes characterized by wind speeds below 1 m/s and relative humidity exceeding 65%, with mean PM2.5 concentrations ranging from 97 to 115 $\mu g/m^3$. A transition to ventilated regimes increases wind speed to >1.2 m/s and reduces PM2.5 by approximately 35-40%, even without any emission intervention. Similar stagnation-driven behaviour is observed in Patna, where dominant regimes exhibit wind speeds as low as 0.5 m/s with PM2.5 concentrations exceeding 80 $\mu g/m^3$. These results provide quantitative justification for automatic activation of control measures based on meteorological thresholds, rather than waiting for PM2.5 exceedances to occur. NCAP-III should therefore institutionalize forecast-based, meteorology-triggered action plans, enabling preventive intervention during high-risk atmospheric conditions.

3. Climate-Sensitive City Classification

The inter-city contrast observed in this study indicates that air quality performance is strongly modulated by local and regional meteorology, making uniform city classification inadequate. Bengaluru and Chennai maintain annual mean PM2.5 below 31 $\mu g/m^3$ and achieve >90-95% monthly compliance, largely due to favourable dispersion conditions such as persistent ventilation and coastal influence, with wind speeds frequently exceeding 3-4 m/s in Chennai. In contrast, Delhi, Patna, and Kolkata experience persistent stagnation regimes, leading to chronic exceedance even under their cleanest meteorological conditions. Importantly, Delhi and Patna fail to meet standards even during non-peak seasons, indicating structural meteorological disadvantage. These findings suggest that NCAP-III must move toward a climate-sensitive city classification, distinguishing stagnation-prone cities from ventilated ones, and assigning stricter targets, enhanced funding, and stronger institutional support to high-risk regions.

4.Re-weight Compliance Assessment

Compliance heatmaps show that monsoon-driven improvements dominate annual compliance statistics across all cities, creating a misleading picture of policy effectiveness. All six cities recorded near-100% compliance during July-September, coinciding with high rainfall, stronger winds, and enhanced boundary-layer mixing. However, this meteorology-driven compliance is temporary and does not reflect emission reductions. In contrast, winter months exhibit widespread failure, with Delhi and Patna showing near-total non-compliance and Kolkata and Mumbai experiencing sharp seasonal deterioration. These results indicate that equal weighting of all months inflates perceived success under annual metrics. NCAP-III should therefore adopt winter-weighted or seasonally adjusted compliance indicators, or alternatively exclude monsoon months from performance evaluation, to better reflect population exposure and public-health risk.

5. Advance the Pollution Control Calendar

Monthly PM2.5 analysis shows that pollution escalation begins well before peak winter, particularly during the post-monsoon transition. In Delhi, post-monsoon seasonal means exceeded 170 µg/m³ in 2024 and remained above 150 µg/m³ in 2025, with November consistently emerging as one of the most polluted months. Similar early-season deterioration is observed in Kolkata and Mumbai, where post-monsoon PM2.5 increased in 2025 despite improvements earlier in the year. These findings indicate that current emergency responses are initiated too late, after pollution has already accumulated under stagnant conditions. NCAP-III must therefore mandate preventive and restrictive measures starting in October, aligned with the onset of adverse meteorology, rather than reactive responses during extreme winter episodes.

6. Strengthen Regional / Airshed-Based Governance

Wind-direction and regime analysis demonstrates that city-level pollution is strongly influenced by regional transport and shared meteorological conditions, particularly across the Indo-Gangetic Plain. Delhi, Patna, and Kolkata repeatedly experience pollution episodes under regimes characterized by weak winds and consistent directional flow, indicating cross-boundary influence that cannot be addressed through isolated city actions. The persistence of high PM2.5 even during local emission control periods further underscores the limitation of city-centric approaches. These results provide strong scientific support for formal integration of airshed-based planning under NCAP-III, with coordinated regional emission control, shared accountability mechanisms, and synchronized seasonal action plans.

7. Track Regime-Specific Outcomes

The clustering analysis shows that even the cleanest meteorological regimes in Delhi and Patna maintain PM2.5 levels near or above national standards (≈72 µg/m³ in Delhi and ≈38 µg/m³ in Patna), highlighting the structural nature of pollution in these cities. At the same time, the frequency and duration of highly polluted regimes dominate annual exposure. This suggests that evaluating success solely through long-term concentration trends overlooks the persistence and recurrence of high-risk atmospheric conditions. NCAP-III should therefore incorporate regime-specific indicators, such as reductions in the number of stagnation days or duration of high-risk clusters, to more accurately capture progress toward sustainable air quality improvement.

CLIMATE TRENDS