Beyond city limits:

A satellite-based PM2.5 assessment across India's airsheds, states, and districts

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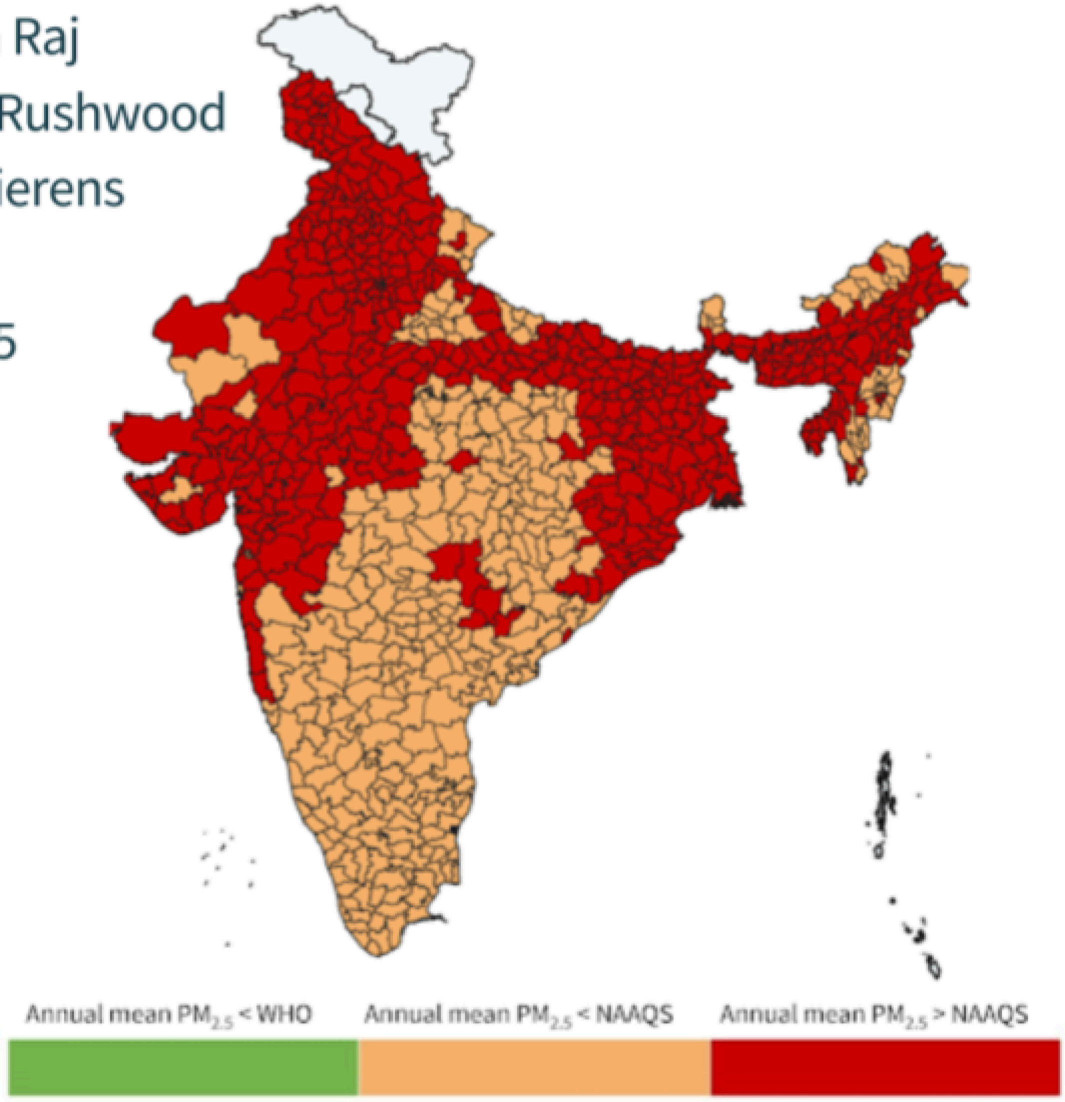

CREA

CREA is an independent research organization focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution.

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About CREA

The Centre for Research on Energy and Clean Air (CREA) is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution. CREA uses scientific data, research, and evidence to support the efforts of governments, companies, and campaigning organisations worldwide in their efforts to move towards clean energy and clean air, believing that effective research and communication are the keys to successful policies, investment decisions, and advocacy efforts. CREA was founded in Helsinki and has staff in several Asian and European countries.

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Beyond city limits: A satellite-based $PM_{2.5}$ assessment across India's airsheds, states, and districts

Key Findings

This report applies a novel machine learning algorithm to derive estimates of population-weighted $PM_{2.5}$ concentrations for India using ground-level air quality measurements and remote sensing data.

District level

- 60% of India's 749 districts breach the annual National Ambient Air Quality Standard (NAAQS) of 40 µg/m^3, with no district meeting World Health Organisation (WHO) $PM_{2.5}$ guideline of 5 µg/m^3.
- Delhi, Tripura, Punjab, Haryana, Himachal Pradesh, Meghalaya, and Chandigarh maintained 100% district-level exceedance in all seasons except for monsoon.
- The top 50 most polluted districts are mostly concentrated in four states (Delhi, Assam, Haryana, and Bihar), indicating clear opportunities for targeted interventions.

State level

- All 33 states and union territories considered in the report exceed the WHO guideline, with 28 states also breaching India's NAAQS.
- Delhi ranked as the most polluted state/union territory with an annual mean $PM_{2.5}$ concentration of 101 µg/m^3, 2.5 times the NAAQS and 20 times the WHO guideline.
- State-level $PM_{2.5}$ averages can mask several local hotspots. For example, Maharashtra's annual $PM_{2.5}$ average was just at the NAAQS threshold, but 14 districts exceed the NAAQS, including Chandrapur with dense clusters of coal-based industries and power plants.

Airshed level

- The Indo-Gangetic airshed remains the most polluted region in the country, consistently non-compliant during winter, summer, and post-monsoon season.
- An emerging concern is the Northeast airshed's year-round air quality challenges, with Assam and Tripura maintaining elevated $PM_{2.5}$ concentrations throughout the year.
- Most airsheds were below $PM_{2.5}$ standards during the monsoon due to atmospheric cleansing, except the Assam–Tripura airshed. But the quick return to non-compliance post-monsoon shows that baseline emissions, not meteorology, are the real problem.

Introduction

India's air quality management needs comprehensive pollution data that includes rural, peri-urban, and smaller cities, not just large metropolitan areas. Satellite-based $PM_{2.5}$ monitoring provides consistent, high-resolution data to assess air pollution across states, districts, and airsheds. While ground monitoring under the National Clean Air Programme (NCAP) and National Air Quality Monitoring Programme (NAMP) is growing, it remains uneven and focused mainly on urban centers, missing key exposure areas elsewhere.

Satellite estimates, combined with ground data and atmospheric models, fill these gaps by providing consistent coverage that captures pollution hotspots, regional trends, and pollution transport beyond administrative borders. This approach supports more accurate assessments of exposure inequalities at the district level and identification of common pollution sources across airsheds like the Indo-Gangetic Plain.

In this assessment, we use satellite-derived $PM_{2.5}$ estimates generated using the machine-learning framework of Kawano et al. (2025). Daily gridded values are aggregated into annual and seasonal means, and population data from NASA SEDAC's GPWv4 are used to compute population-weighted $PM_{2.5}$ levels.

The findings from this satellite-based $PM_{2.5}$ assessment offer important insights for policymakers, helping to guide targeted interventions, plan resource allocation to the most affected regions, and support coordinated efforts across states. This report presents a detailed analysis of annual and seasonal $PM_{2.5}$ concentration across states, districts, and airsheds, serving as a basis for informed policy decisions and tracking progress toward cleaner air.

District-wise analysis

Annual $PM_{2.5}$ concentration

Annual population-weighted $PM_{2.5}$ concentrations across India's districts show significant disparity, ranging from as low as 21 µg/m^3 in Tiruppur, Tamil Nadu, to a high of 112 µg/m^3 in the North-west district of Delhi.

Overall, 60% of districts (447 out of 749) exceed the National Ambient Air Quality Standard (NAAQS) for annual $PM_{2.5}$. None of the districts met the World Health Organisation (WHO) guideline of less than 5 µg/m^3 as shown in Figure 1.

The most polluted districts are heavily concentrated in a few states, highlighting regional clustering of severe air quality issues. Delhi (11 districts) and Assam (11 districts) alone account for nearly half of the top 50, followed by Bihar (7) and Haryana (7). Other notable contributors include Uttar Pradesh (4), Tripura (3), Rajasthan (2), West Bengal (2), and single districts from Chandigarh, Meghalaya and Nagaland.

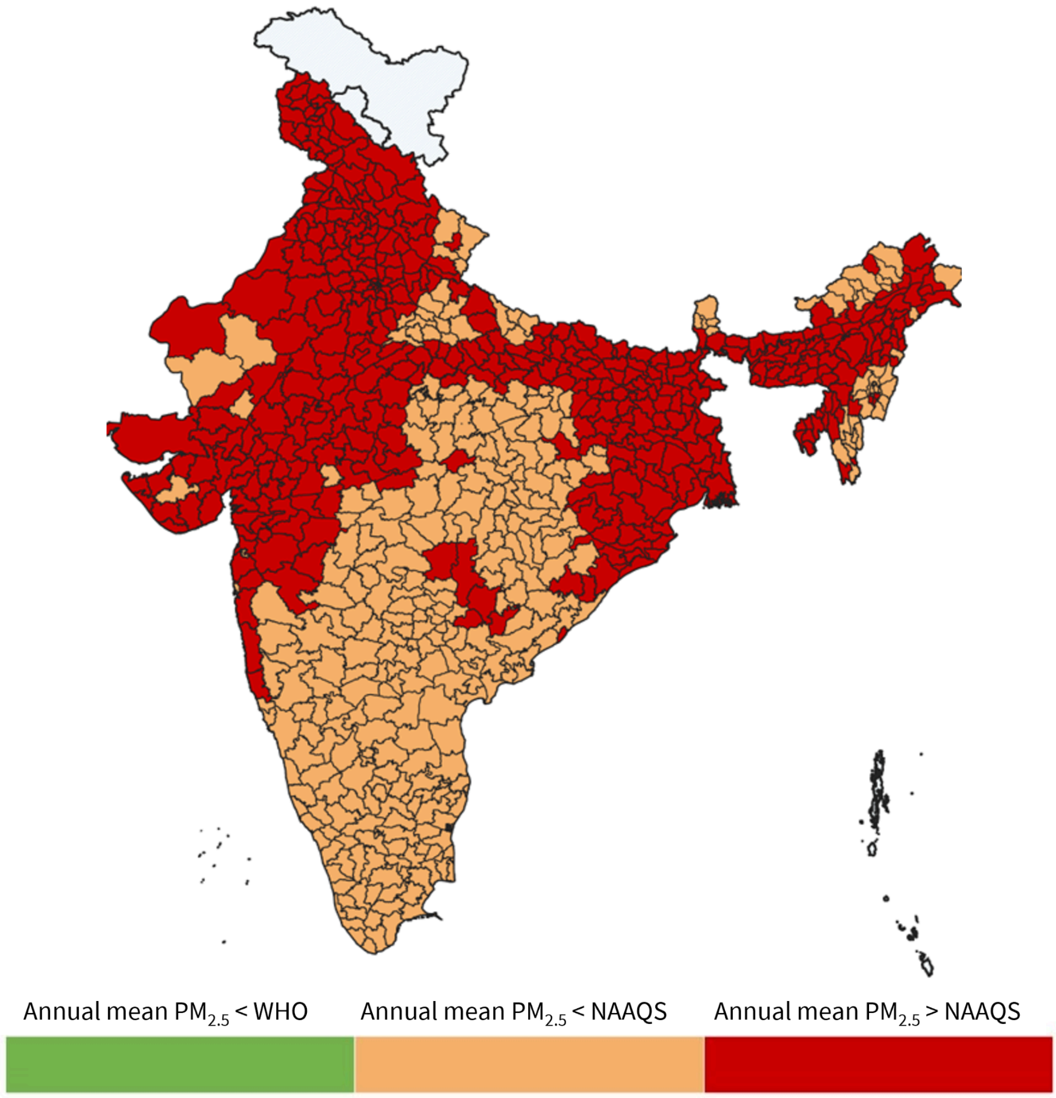

Figure 1. Annual compliance status of Indian districts

Several states are in universal non-compliance, where all monitored districts exceed the NAAQS. These include Delhi, Assam, Punjab, Haryana, Chandigarh, Himachal Pradesh, Meghalaya, Tripura, and Jammu and Kashmir. Several other states show a large majority of districts breaching the norm, such as Bihar (37 of 38), West Bengal (22 of 23), Gujarat (32 of 33), Nagaland (11 of 12), Rajasthan (30 of 33), andJharkhand (21 of 24).

A second group shows mixed performance, where some districts meet the standard but many continue to exceed it. This includes Uttar Pradesh (49 of 75 districts exceeding), Odisha (22 of 30), Madhya Pradesh (27 of 52), and Maharashtra (14 of 36). In the Northeast, Arunachal Pradesh (12 exceed, 13 comply) and Manipur (five exceed, 11 comply) also fall in this transitional category.

At the other end of the spectrum, several states have the majority of their districts below NAAQS, such as Andhra Pradesh, Telangana, Kerala, Sikkim, Goa, Karnataka, and Tamil Nadu.

These contrasting patterns highlight the continued dominance of northern and eastern states in India's $PM_{2.5}$ pollution hotspots, while southern and coastal regions remain relatively cleaner.

In many districts and states, limited monitoring infrastructure makes it difficult to accurately capture real-world exposure. Monitoring stations are often located in cleaner areas, away from industrial zones or busy corridors, which leads to underestimation of actual pollution levels.

For example, an industrial hub situated on the outskirts of a compliant district may appear clean because its nearest monitor is placed in a less polluted suburban zone. Integrating satellite observations with a denser and better-sited monitoring network would correct such biases and yield a more representative picture of air quality across the region.

Delhi's experience illustrates how monitoring density can influence data accuracy. The city's extensive ground network closely aligns with satellite-derived $PM_{2.5}$ estimates, effectively capturing local spatial variations.

In contrast, most states have sparse networks, resulting in potential underestimation of actual concentrations. The analysis suggests that if other states had dense monitoring coverage, satellite-based estimates can be improved. Thus, expanding the ground-monitoring network nationwide is essential.

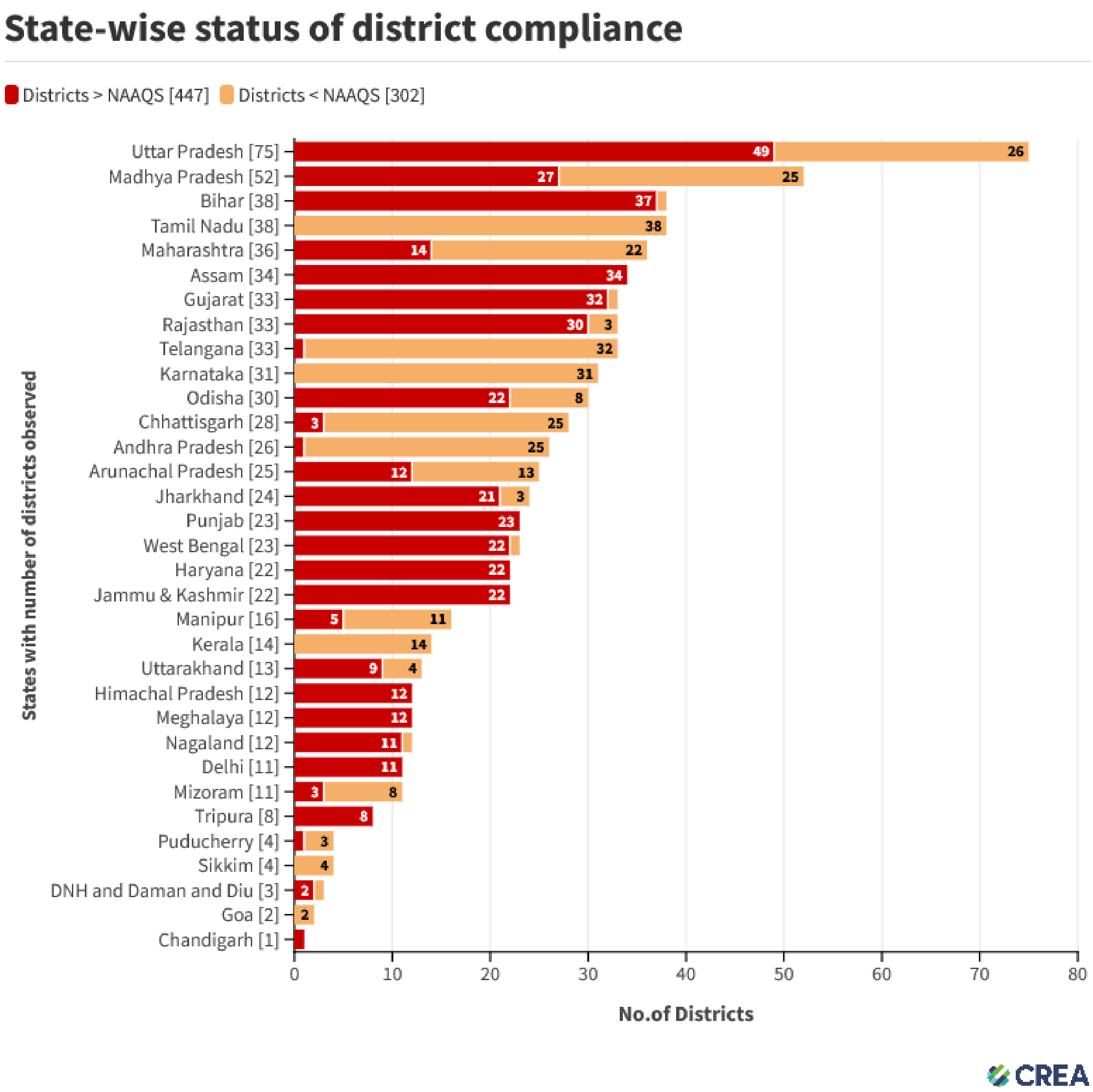

Figure 2. Number of districts in each state meeting or exceeding the NAAQS in 2024

Seasonal trends

Approximately 82% (616 of 749 districts) of India's districts record $PM_{2.5}$ concentrations above the national standard during winter when emissions increase and stagnant weather traps pollutants near the surface. The monsoon season brings significant improvement, reducing exceedance to just 10% of districts (74 of 749), driven primarily by rainfall-induced atmospheric cleansing. However, this relief is temporary. Post-monsoon months see a sharp resurgence, with three out of four districts (566 of 749) again exceeding the standard.

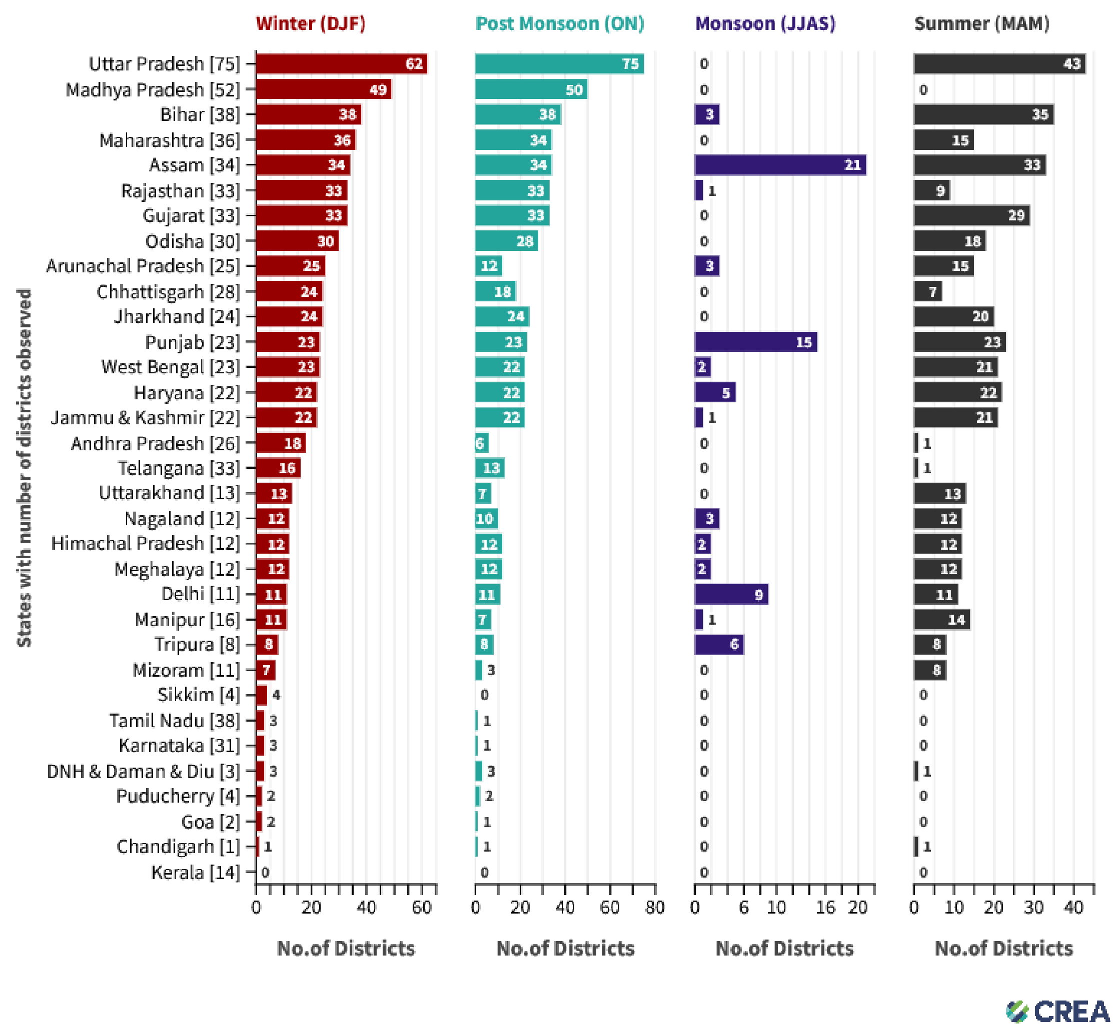

Figure 3. Seasonal shifts in district-level $PM_{2.5}$ exceedance across state

In summer, the situation is mixed, with more than half of districts (405 of 749) exceeding the national limit. Overall, these data indicate that, despite seasonal fluctuations, unhealthy air is a persistent challenge for most of the year.

State-level seasonal patterns of $PM_{2.5}$ exceedance show that winter remains India's pollution peak, with 22 out of 33 states recording 100% of districts above the national standard.

With rising temperatures in summer, most states see declines in the number of exceeding districts. Yet, pollution remains universal in nine states, each reporting 100% district-level exceedance during the season.

Uttar Pradesh and Madhya Pradesh, which have the highest counts of exceeding districts in winter and post-monsoon, experience a full drop to zero exceedance during the monsoon.

In contrast, Assam, Delhi, Punjab, and Tripura remain pollution hotspots year-round, exceeding $PM_{2.5}$ standards even during the monsoon when much of India experiences cleaner air. Assam recorded 21 districts, Delhi nine, Punjab 15, and Tripura 6 districts exceeding standards during monsoon season, showing that meteorological relief alone is insufficient to overcome their substantial baseline emissions.

Following the monsoon season, the gains rapidly dissipate. The post-monsoon season sees 100% exceedance of districts in 15 states especially located in northern and eastern states. This rebound is driven by a combination of consistent baseline emission load, and episodic events (crop residue burning and festival-related emissions) and slower wind speeds.

State-wise analysis

Annual $PM_{2.5}$ concentration

Of the 33 states and union territories included[1] in this analysis, 28 had at least one district where annual $PM_{2.5}$ levels exceeded the NAAQS of 40 µg/m^3, and 19 had statewide average $PM_{2.5}$ levels above this limit. However, when compared to the WHO standard of 5 µg/m^3, not a single state complied.

- Delhi recorded the highest pollution levels with an annual mean $PM_{2.5}$ concentration of 101 µg/m^3, 2.5 times the Indian standard and 20 times the WHO guideline.
- The pollution crisis extends across northern India, with the average $PM_{2.5}$ concentrations in all states in these regions including Delhi, Chandigarh, Haryana,

[1] Some regions could not be studied due to limitations in data availability, see Methodology for details.

Punjab, Uttar Pradesh, Himachal Pradesh, Uttarakhand, and Jammu & Kashmir exceeding the NAAQS. This concentration of pollution aligns with their location in the Indo-Gangetic Plain.

- The eastern and northeastern states showed similarly concerning levels, with $PM_{2.5}$ average concentrations in Bihar, West Bengal, Jharkhand, Odisha, Assam, Meghalaya, Nagaland, Tripura, and Arunachal Pradesh all above the NAAQS.
- Among western states, the mean concentrations in Rajasthan and Gujarat exceeded the annual national standard.
- Southern India presented the lowest $PM_{2.5}$ values. Puducherry recorded the lowest concentration at 25 µg/m^3, followed by Tamil Nadu, Karnataka, Sikkim, Telangana, Kerala, and Andhra Pradesh.

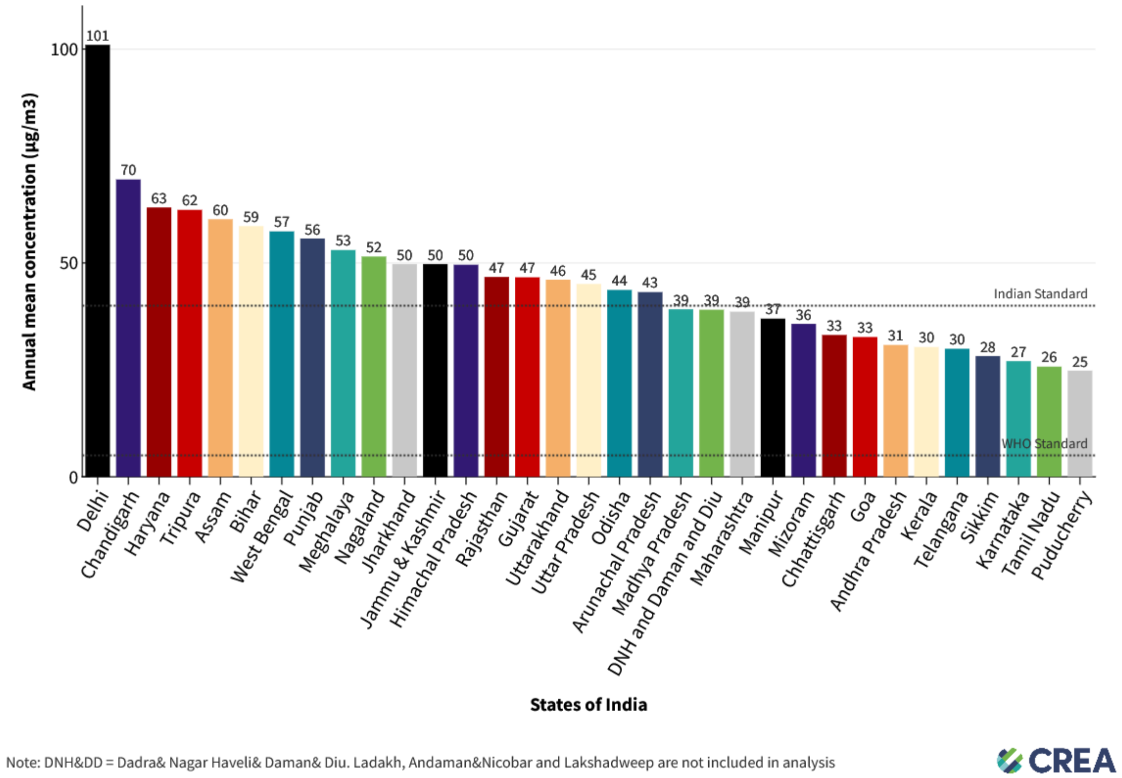

Figure 4. State-wise annual mean $PM_{2.5}$ concentrations during 2024

At the state level, $PM_{2.5}$ concentrations may appear lower because the average combines both high- and low-pollution districts. However, this averaging can mask severe local hotspots.

For instance, Maharashtra's overall $PM_{2.5}$ levels in 2024 were just at the NAAQS threshold, yet districts such as Chandrapur consistently exceed the annual $PM_{2.5}$ standard due to dense clusters of coal-based industries and power plants. Therefore, state-level averages must be interpreted carefully to avoid overlooking district-level pollution realities.

Even in states where $PM_{2.5}$ levels are below the NAAQS, they remain above the WHO guideline. This relative cleanliness should not lead to complacency. Instead, it offers an opportunity to set differentiated or region-specific targets, allowing southern states to adopt stricter interim limits aligned with the WHO's standard. Such regionally tailored benchmarks would enable progressive improvement in cleaner areas while maintaining equity across states facing different baseline pollution levels.

Seasonal $PM_{2.5}$ concentration

Delhi consistently ranks as the most polluted state across all seasons highlighting the capital's year-round air quality crisis. Beyond Delhi, the composition of the top five most polluted states shifts with the seasons, revealing distinct regional pollution patterns.

The Indo-Gangetic Plain states feature prominently: Chandigarh appears in the top five during three seasons (winter, summer, and post-monsoon), while West Bengal also ranks among the worst across winter and post-monsoon seasons.

Punjab and Haryana emerged as major air-pollution concerns, with Punjab during the monsoon and post-monsoon periods and Haryana during the summer and post-monsoon periods.

The northeastern states present an unexpected pollution hotspot, with Assam and Tripura featuring in the top five in three seasons (winter, summer, and monsoon).

This persistent presence of northeastern states in the most polluted category challenges the conventional focus on northern plains and highlights the need for region-specific air quality interventions.

The recurring presence of these states across multiple seasons emphasises that India's air pollution crisis requires sustained, year-round policy action rather than seasonal emergency measures like the Graded Response Action Plan (GRAP).

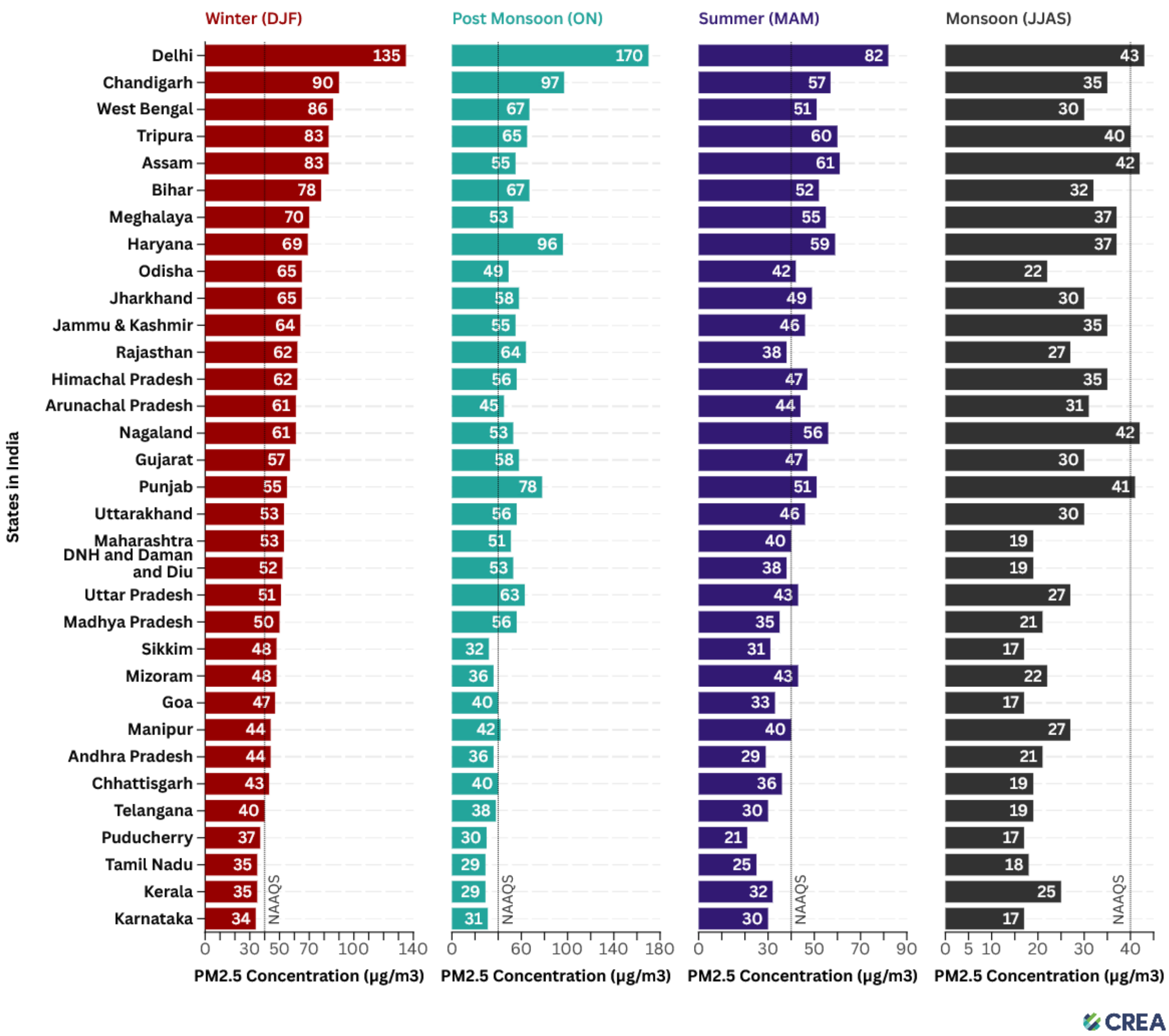

Figure 5. Seasonal state-wise $PM_{2.5}$ concentration

Airshed-level analysis

An airshed is simply a region of the atmosphere where air tends to move and mix in a common pattern, often shaped by local geography like mountains, valleys, or weather conditions such as wind and rain. This means that pollution released anywhere within an airshed can travel and affect air quality across the whole area, regardless of city or state boundaries.

Airshed boundaries do not stay fixed throughout the year because they depend on changing weather and wind directions, which shift with the seasons. For example, the direction and strength of monsoon winds, winter temperature inversions, or heavy summer heat can all reshape how air masses move, causing the borders of each airshed to expand, shrink, or split.

Seasonal analysis of these shifting airsheds shows how each region's $PM_{2.5}$ varies through the year, directly informing more targeted solutions for India's unique challenges.

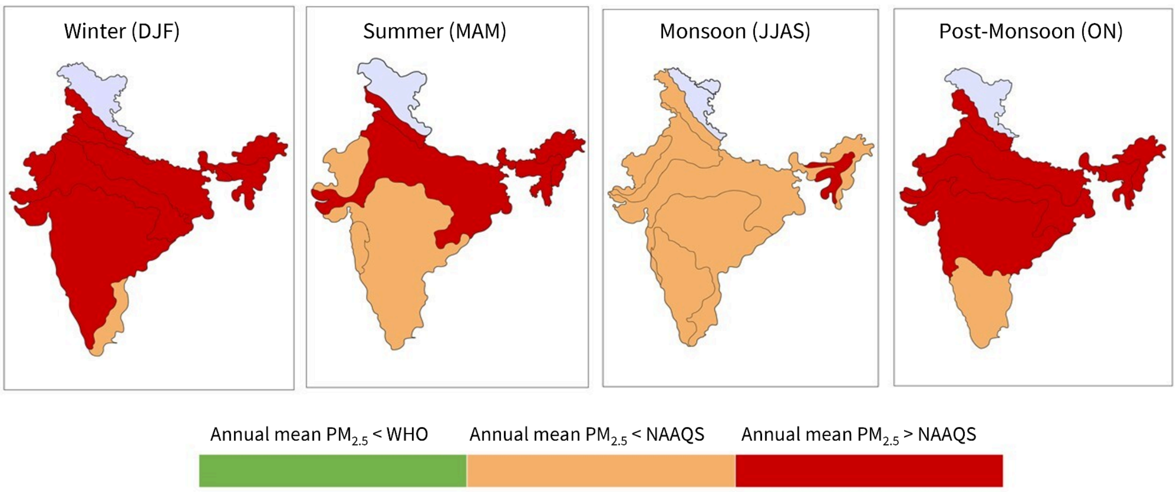

Figure 6. Seasonal compliance of airsheds

The visualization (Figure 6) of seasonal $PM_{2.5}$ levels across airsheds shows that during winter, most of India experiences concentrations exceeding the national standard, indicated by extensive red-shaded areas. This seasonal air quality decline is especially severe in the northern and central airsheds, driven by meteorological factors such as stagnant air, temperature inversions, and high-baseline emission load. Only a small part of southern India avoids these winter pollution levels, with $PM_{2.5}$ concentrations below the NAAQS.

As the country transitions into summer, there is a reduction in $PM_{2.5}$ in the southern, western, and central airsheds. Nonetheless, northern and eastern airsheds continue to struggle, with widespread exceedances remaining persistent, particularly in the Indo-Gangetic Plain. This demonstrates the region's chronic issues with high pollution even outside the typical winter peak.

The arrival of the monsoon brings the most improvement, with nearly all airshed regions across the country were below NAAQS, with exception of some north-eastern states. Rainfall effectively cleanses the air, yielding the best overall air quality of the year. However, this respite is short-lived. Once the rains subside and the post-monsoon period sets in, pollution levels rise swiftly again, especially in northern and central air sheds.

The way forward

This satellite-based $PM_{2.5}$ analysis highlights that India's air pollution challenge extends well beyond city limits and demands a broader, data-driven policy approach. To move toward sustained air quality improvement, the following policy directions are critical:

1. **Expand clean air planning beyond non-attainment cities:** With over half of Indian districts exceeding $PM_{2.5}$ standards, clean air planning must extend beyond the current list of non-attainment cities. States should develop district-level air quality action plans, guided by satellite data to identify hotspots, prioritise high-exposure populations, and allocate mitigation resources efficiently.
2. **Satellite data in air quality governance**: Satellite-derived $PM_{2.5}$ data should be formally integrated into NCAP for spatially comprehensive assessment and performance tracking. Establishing protocols for validation, periodic updates, and public dissemination of satellite-based estimates will strengthen transparency and enable real-time decision-making in areas lacking ground monitors.
3. **Target regional and sectoral emission sources:** The persistence of high $PM_{2.5}$ across the Indo-Gangetic Plain and northeastern states highlights the need to address major regional source clusters such as power generation, industrial activity, biomass burning, and transport.
4. **Incentivise state-level accountability and performance tracking:** States should be evaluated on measurable progress toward $PM_{2.5}$ reduction using standardised indicators derived from both satellite and ground data. Linking clean air performance to fiscal incentives under NCAP can drive accountability.
5. **Adopt airshed-based management frameworks:** Pollution travels across administrative borders, linking urban, peri-urban, and rural regions. Implementing airshed-level mitigation measures under NCAP can help align actions across neighboring states and districts. Coordinated emission reduction plans, joint

monitoring systems, and accountability mechanisms are essential for addressing transboundary pollution.

Methodology

The $PM_{2.5}$ data were generated following the machine learning framework developed by Kawano et al. (2025). Daily $PM_{2.5}$ values were generated at 10 km resolution for all of India using satellite data for aerosol optical depth, NO_2 and CO, as well as weather data and other auxiliary datasets in a two-step modelling approach. We followed the method as described in Kawano et al. (2025), and trained the model and produced the $PM_{2.5}$ values for the time period of September 2018 to March 2025.

Our implementation achieves a similar level of accuracy, evaluated against air quality monitoring station data, with R^2=0.60 and RMSE=27.14 µg/m^3 for daily values, compared to the R^2=0.67 and RMSE=27.7 µg/m^3 reported by Kawano et al. (2025). From the daily values, seasonal and annual mean values were calculated for each grid point for the year 2024 – all except for the winter season data from December 2024 to February 2025 were used. The mean of each district, state, or airshed was then calculated as an area-weighted mean from the gridded $PM_{2.5}$ values. Population data from NASA SEDAC's GPWv4 Population Count dataset was used to derive population-weighted $PM_{2.5}$ levels. The gridded population counts enable calculating population-weighted means from the $PM_{2.5}$ concentrations.

Shapefiles delineating state and district administrative boundaries were sourced from Guttikunda (2024), while the airshed shapefile was obtained from Kumar et al. (2025). Ladakh, Andaman and Nicobar Islands, and Lakshadweep were excluded from the analysis due to insufficient ground monitoring data during the study period of 2024. The remaining 33 states and union territories, covering 749 districts, were included in the assessment. Seasonal airsheds varying between 9 and 11 across different seasons were also analysed to examine regional variations in $PM_{2.5}$ concentrations. In this analysis, seasons are defined as: winter (December 2024 - February 2025), summer (March 2024 - May 2024), monsoon (June 2024 - September 2024), and post-monsoon (October 2024 - November 2024).

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