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ORIGINAL ARTICLE

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Characterization of particulate matter ratios and dust resuspension dynamics in the urban airshed of Bengaluru, Karnataka

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ABSTRACT

In rapidly urbanizing tropical megacities, source apportionment of particulate matter is often complicated by the interaction between combustion emissions and crustal resuspension, and Bengaluru represents this challenge. This study characterizes the city's airshed during 2018–2024 using high-resolution data from 13 Continuous Ambient Air Quality Monitoring Stations (CAAQMS) obtained from the Central Pollution Control Board (CPCB) open-access portal. Three complementary approaches were applied: stoichiometric decoupling of $PM_{2.5}$ and PM_{10} fractions, unsupervised k-Means clustering to identify pollution regimes, and Principal Component Analysis (PCA) with Varimax rotation to distinguish dominant sources. Clustering identified three distinct regimes: a combustion-dominated winter regime ($Rf/c > 0.65$) strongly associated with traffic emissions, a baseline urban regime representing equilibrium conditions, and a dust-dominated pre-monsoon regime (March–May). During the pre-monsoon period, the $PM_{2.5}/PM_{10}$ ratio declined to approximately 0.44 due to increased coarse particulate matter (PMcoarse). PCA corroborated this separation by identifying an independent Resuspension Factor explaining 21.2% of the total variance. Regression analysis further supported these findings, with the $PM_{2.5}$–PM_{10} slope decreasing sharply in summer ($\beta = 0.38$, $R^2 = 0.51$), indicating coarse dust accumulation independent of the fine-particle baseline. Elevated weekend coarse particulate concentrations despite reduced traffic further confirmed persistent road dust reservoirs. These findings demonstrate that effective air-quality management should complement tailpipe-emission controls with non-exhaust measures, including systematic vacuum road sweeping, to mitigate Bengaluru's resuspension-driven summer particulate peak.

KEY WORDS

PM ratios; Coarse fraction; Dust resuspension; Airshed coupling; k-Means clustering; Bengaluru

ARTICLE HISTORY

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Introduction

The bimodal nature of urban aerosol loads

As cities across the Global South grow denser, their atmospheric chemistry shifts. PM accumulates chronically, pushing concentrations past global health safety thresholds [1]. That burden is not chemically uniform; it splits into two modes, primary combustion aerosols ($PM_{2.5}$) and mechanically generated particles (PMcoarse). Regulators have long targeted the fine fraction first, and for good reason: it is acutely toxic to the heart and lungs and slips past the alveolar barrier [2]. The coarse fraction has drawn far less scrutiny, even though it carries a large share of the total mass.

The coarse mode covers particles between 2.5 and 10 µm in aerodynamic diameter, and resuspension is what governs its behavior. Crustal material, tire-abrasion particles, and road silt are lofted into the planetary boundary layer by wind shear and by the turbulence that moving vehicles generate [3]. In Indian megacities, the source mechanisms are hard to separate, because the urban canyon effect traps tailpipe exhaust and resuspended dust together in the breathing zone under poor ventilation [4]. So, a management strategy built only around fleet modernization, such as the shift to BS-VI fuel standards, reaches the combustion-derived fraction and little else, and the non-exhaust component is left largely untouched [5].

Anthropogenic stressors in Bengaluru

Bengaluru sits on the Deccan Plateau at about 920 m elevation, and that setting makes it a useful test case. Unlike the alluvial plains of the Indo-Gangetic belt, its semi-arid climate favours the mechanical suspension of crustal dust instead [6]. Vehicle numbers have since climbed steeply, and the scale of that growth is hard to overstate. By late 2024 the metropolitan fleet exceeded 1.23 crore (12.3 million), and with over 23.1 lakh registered private cars the city had overtaken New Delhi in private-vehicle ownership [7]. Over the same years the municipal road network grew to roughly 12,878 km of arterial and sub-arterial corridors, which is a vast surface reservoir for fugitive emissions [8].

Policy has pushed electric vehicle (EV) registrations up 18-fold since 2020, and the fleet passed 100,000 units in 2024 [9]. But that is still under 1% of all vehicles on the road. Electrification removes the tailpipe stream (NO_x, CO); it does nothing for the non-exhaust stream. And there is a twist: EVs are heavier, and recent tribological work suggests the extra curb weight can raise tire wear and road-surface abrasion, which keeps feeding the coarse dust burden [10,11]. With roughly 2,700 new vehicles entering the roads each day as of late 2024, the mechanical turbulence stirred up by all that movement remains a leading driver of local air quality decline [12].

Research gap and objectives

Non-exhaust sources clearly matter to the urban airshed, yet the Bengaluru literature has mostly gone elsewhere: to the

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chemical speciation of $PM_{2.5}$, or to long-term trends in bulk concentrations [13]. A specific and telling gap runs right through the wider Indian literature as well. Few studies have decoupled the exhaust and non-exhaust fractions mathematically, using ratio-based stoichiometric measures applied across multi-year, multi-station records [14-16]. Some recent work has started to examine non-exhaust and road-dust emissions in cities, Indian ones included [13,17]. But no earlier study has paired unsupervised machine learning (k-Means clustering) with PCA to classify atmospheric stability regimes across the whole Bengaluru airshed over seven years, and none has quantified the road-dust reservoir effect through weekend–weekday NO_2 differentials as a traffic proxy in this setting [18-20]. Leave that decoupling undone and policy risks going astray, pouring money into combustion control while municipal fixes such as vacuum-assisted road sweeping go unfunded.

Four objectives follow directly from the gap identified above, and each target one facet of the problem. The first is to decouple the coarse dust fraction (PMcoarse) from total aerosol mass using high-resolution hourly data. The second is to sort the city's airshed into distinct stability regimes through unsupervised k-Means clustering. The third is to quantify how dust resuspension is modulated across seasons and across the day, and to test its independence from combustion sources with non-parametric correlation analysis. The last is to turn these findings into evidence-based recommendations for Zonal Air Quality Management (ZAQM).

Materials and Methods

Study area

The study area is the Greater Bengaluru Metropolitan Area (12°58′ N, 77°35′ E), a fast-growing agglomeration on the Mysore Plateau at a mean elevation of 920 m above mean sea level (MSL). Its climate is tropical savanna, with a clear split between wet and dry seasons. The terrain itself does much of the work here, because the elevated relief of the Deccan Plateau lets wind speeds rise through the pre-monsoon season (March–May), and that wind, paired with low relative humidity, is enough to lift crustal matter mechanically [6,21]. On the ground, a dense 12,878 km road network carries a vehicle load that often stalls into stop-and-go flow. To map the spatiotemporal footprint of these emissions, the study draws on high-resolution data from 13 CAAQMS. The stations are grouped by land use, across industrial, kerbside, and residential zones, so that the city's varied microenvironments are all represented (Figure 1).

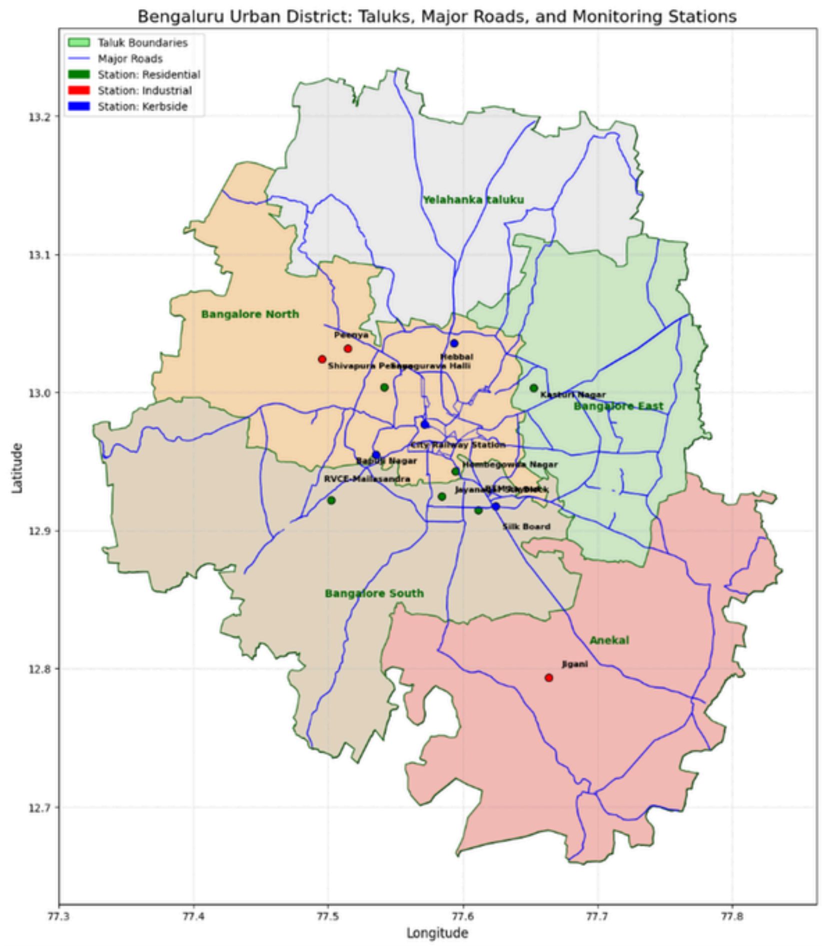

Figure 1. Location map of the 13 CAAQMS monitoring stations in the Greater Bengaluru Metropolitan Area, stratified by land-use category (Industrial, Kerbside, Residential). Data source: CPCB CAAQMS network (2018–2024).

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Data acquisition

Hourly concentrations of PM_{10}, $PM_{2.5}$ and NO_2 were obtained from the CPCB, CAAQMS network for January 1, 2018 to December 31, 2024 [22]. These records are openly available to the public, and can be reached through the CPCB's CAAQMS portal at: https://app.cpcbccr.com/AQI_India/ and the data-download interface at https://airquality.cpcb.gov.in/ (accessed November 2024). Station-level files were downloaded as comma-separated values (CSV) and merged into a single panel dataset before analysis. Figure 1 shows the full set of stations together with their land-use classifications.

Data preprocessing and quality assurance

Before any statistics were run, the data passed through a multi-stage quality assurance (QA/QC) protocol, following accepted practice for ambient monitoring records, and the five stages of that protocol are set out in Table 1 [23,24]. Nothing further was done to the series beyond this, no seasonal decomposition and no normalization, because raw hourly concentrations are the correct input for the stoichiometric ratios and the clustering that follow in the Mathematical Framework section. The one exception is internal: z-score standardization was applied inside the clustering and PCA routines to stop scale-dependent bias, as described below.

Table 1. Five-stage data preprocessing and quality assurance protocol applied to the CAAQMS dataset (2018–2024).

Stage	Action	Rationale
Stage 1: Instrument flag removal	Records flagged by CPCB as calibration periods, power outages, or sensor faults excluded (~2.3% of raw records).	Eliminates known non-ambient measurement artefacts at source.
Stage 2: Physical range filtering	Observations where $PM_{2.5} > PM_{10}$ excluded as stoichiometric violations.	Physically impossible; indicative of sensor malfunction or data-entry error.
Stage 3: Outlier detection	Values exceeding 3σ from the rolling 24-hour mean flagged and removed.	Removes transient spikes (e.g., fires, construction) not representative of ambient conditions.
Stage 4: Missing-value treatment	Gaps <6 consecutive hours imputed by linear interpolation. Gaps >6 hours excluded entirely. Stations with annual data capture <75% excluded from trend analysis for that year.	Balances temporal continuity with preservation of data fidelity.
Stage 5: Completeness summary	Overall data completeness after QA/QC: 87.4% across all 13 stations for 2018–2024.	Exceeds the 75% minimum threshold recommended for regulatory-grade trend analysis (U.S. EPA, 2016).

Mathematical framework

Coarse fraction decoupling

To isolate the mass contribution of resuspension sources, the coarse fraction PM_{coarse} was derived by stoichiometrically subtracting the fine mode from the bulk mass [25,26]:

$$\mathbf{PM_{coarse} = PM_{10} - PM_{2.5}}$$

Concurrently, the fine-to-coarse ratio $R_{f/c}$ was calculated to serve as a dimensionless indicator of the dominant pollution regime:

$$\mathbf{R_{f/c} = PM_{2.5} / PM_{10}}$$

Seasonal regression model

The Ordinary Least Squares (OLS) linear regression model was used to quantify inter-modal coupling strength across different meteorological seasons. The slope β of the regression line serves as a proxy for the regional airshed signature:

$$\mathbf{PM_{2.5} = \beta \cdot PM_{10} + \varepsilon}$$

where a lower β indicates a decoupling of fine and coarse modes, characteristic of dust-dominated events.

Unsupervised classification (k-Means clustering)

To classify the airshed into stability regimes without imposing prior assumptions, the k-Means algorithm was used. It partitions the n hourly observations into k clusters by minimizing the within-cluster sum of squares (WCSS):

$$\mathbf{J = \Sigma_j \Sigma_i ||x_{ij} - c_j||^2}$$

The optimal cluster count (k = 3) came from the Elbow Method, which plots WCSS against k and marks the point where each added cluster buys little extra explained variance. Three variables made up the feature vector: $PM_{2.5}$ (µg/m^3), PM_{10} (µg/m^3), and $R_{f/c}$ (dimensionless). Each was standardized to unit variance (z-score normalization) before clustering so that no variable dominated on scale alone.

Dimensionality reduction (PCA)

To surface the latent source factors behind the variance in the airshed, PCA with Varimax orthogonal rotation was used. Varimax was chosen because it drives toward the simplest factor structure, one in which each variable loads mainly on a single component [27]. Four pollutants entered the input matrix, namely PM2.5, PM10, PMcoarse, and NO2, and each was standardized to unit variance (z-score normalization) before extraction. Components with eigenvalues above 1.0 were kept under the Kaiser criterion, which left two components accounting for 82.4% of total variance. PCA recasts the correlated pollutant variables as a smaller set of uncorrelated Principal Components (PCs):

$$Z^k = \Sigma_i a^k_i X_i$$

Where Z^k is the component score and a^k_i is the factor loading. Two components were retained: PC1 (Traffic Factor), identified by high loadings of NO_2 and $PM_{2.5}$; and PC_2 (Resuspension Factor), identified by high loadings of PM_{10} and PM_{coarse}, strictly isolated from gaseous pollutants.

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Spatial heterogeneity (COD) and MDS

The COD was computed for every station pair to gauge how spatially heterogeneous the network is. That pairwise dissimilarity matrix then fed a non-metric Multidimensional Scaling (MDS), which resolves the network's structural redundancy in two-dimensional Euclidean space. A stress value of 0.11 marks the two-dimensional ordination as reliable [28].

Results and Discussion

Longitudinal dynamics: The asymmetry of air quality trajectories

Across the seven-year record (2018–2024), air quality in the Greater Bengaluru airshed did not move as one. The Mann–Kendall trend analysis (Figure 2a) breaks the usual picture of uniform urban pollution growth, and instead shows compliance pathways pulling apart into a two-speed city. Peenya carries the industrial signal, and it is falling: $PM_{2.5}$ there shows a strong, statistically significant decline (Sen's Slope = −2.75 µg m^{-3} $year^{-1}$; $p < 0.01$). That runs against the pattern in Delhi, where industrial corridors tend to stay out of compliance with high baseline loads [15]. The Peenya decline lines up closely with the boiler-fuel standardization and stack-monitoring enforcement that the Karnataka State Pollution Control Board (KSPCB) stepped up after 2019, and it echoes the national-scale drop in industrial $PM_{2.5}$ across Tier-1 cities under the National Clean Air Programme [29].

The residential and mixed-use sectors move the other way, and not for the better. BTM Layout shows a statistically significant rise in ammonia (NH3) of +1.44 µg m−3 year−1, and NH3 is not a combustion product at all. In cities it usually flags biological decomposition, so this quiet climb points back to gaps in solid-waste handling and untreated sewage, both of which seep secondary aerosol precursors into the air [30]. Delhi has shown the same enrichment, where gaseous ammonia fed secondary inorganic aerosol formation under comparable urban metabolism pressures [30]. Bengaluru now appears to be walking a path already mapped across the Indo-Gangetic Plain.

The urban sprawl effect and compliance hotspots

Trends give the direction; exceedance frequency gives the day-to-day burden (Figure 2b). The worst offender in the network is not at all where one might expect it to be. RVCE Mailasandra breaches the NAAQS threshold (>60 µg/m^3) on 89.9% of monitored days, the highest in the network. That undercuts the city-centre hypothesis, which places the peak pollution in the central business district. What Bengaluru shows instead is an urban sprawl effect: the heaviest particulate loads sit on the fast-urbanizing periphery. Those fringes have few paved roads and plenty of active construction, so crustal dust saturates the local air whatever the traffic count [31]. The pattern matches western India, where crustal and construction dust dominates the coarse fraction, and it fits the wider finding that road dust and construction rank among the main PM_{10} drivers in fast-growing Indian cities [4,32].

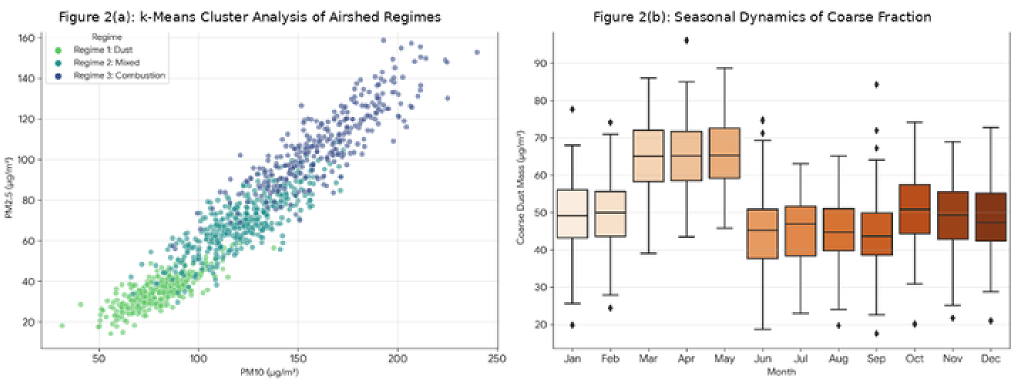

Figure 2. (a) Mann–Kendall trend analysis of $PM_{2.5}$ concentrations across 13 CAAQMS stations in Bengaluru (2018–2024), illustrating the divergent two-speed air quality trajectory between the Peenya industrial cluster (Sen's Slope = −2.75 µg m^{-3} $year^{-1}$; $p < 0.01$) and residential/mixed-use zones. (b) Exceedance-frequency analysis showing the percentage of monitored days on which PM_{10} concentrations exceeded the NAAQS threshold (>60 µg/m^3) at each station, identifying RVCE Mailasandra as the primary non-compliance hotspot (89.9% violation days). Data source: CPCB CAAQMS network (2018–2024).

The fractured airshed: Quantification of spatial heterogeneity

Does a city breathe as one well-mixed reactor, or as a patchwork of isolated microclimates? For Bengaluru the COD settles the question in favour of the patchwork (Figure 3a). Under the threshold set by Wilson et al., a COD above 0.20 marks a spatially heterogeneous environment, and the Peenya-Jayanagar pair returns 0.42, sitting well past that line [33]. Delhi shows the same kind of intra-urban split, with coarse- and fine-fraction source contributions diverging sharply between sites, as does Mumbai, where site-to-site contrasts in composition track distinct local source mixes; together they argue that these gradients are real and source-driven rather than monitoring artefacts [34,35]. The industrial north, on this evidence, is chemically decoupled from the residential south. Regional wind cannot flatten those differences, and pollution ends up pooling in the low ground through a valley-trapping effect.

MDS and regime identification

The non-metric MDS ordination (Figure 3b) pulls apart the network's structural redundancy, and three statistically distinct regimes fall out of it. The Industrial Regime (red) sits on high baseline particulate loads with little seasonal swing, fed by continuous point sources. The Kerbside Regime (orange) carries high $NO_2/PM_{2.5}$ ratios, the fingerprint of a traffic-dominated profile. The Residential/Background Regime (green) is different again: stations such as Jayanagar and BTM Layout crowd together in Euclidean chemical space, which means they

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are, in effect, sampling one and the same air parcel. That redundancy is worth acting on, because it means future stations would do more good on the unmonitored periphery than packed into an already well-covered core.

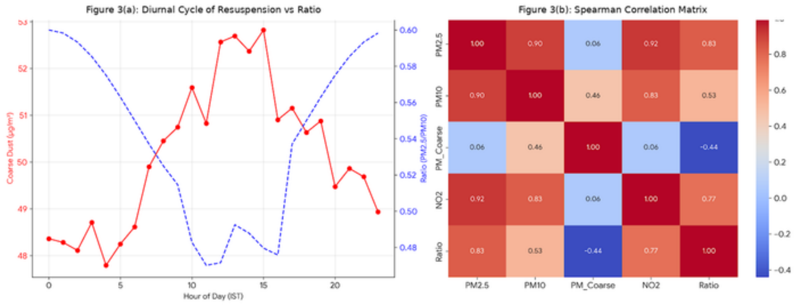

Figure 3. (a) Pairwise COD matrix for all 13 CAAQMS station combinations, with values exceeding 0.20 indicating spatially heterogeneous environments [33]. The Peenya–Jayanagar pair yields the highest COD (0.42), confirming chemical decoupling of the industrial north from the residential south. (b) Non-metric MDS ordination of the 13 CAAQMS stations in two-dimensional Euclidean chemical space (stress = 0.11), resolving three structurally distinct airshed regimes: Industrial (red), Kerbside (orange), and Residential/Background (green). Data source: CPCB CAAQMS network (2018–2024).

k-Means regime centroids

Table 2 sets out the centroids of the three stability regimes from the k-Means run, with the Elbow Method fixing k = 3 as optimal and WCSS levelling off past that point. Regime 1 (Dust-Dominated) holds 34% of the hours and carries the lowest ratio of the three, $PM_{2.5}/PM_{10}$ = 0.44, driven mainly by mechanical resuspension of road dust (PM_{10} centroid 79.30 µg/m^3; PM_{coarse} centroid 44.61 µg/m^3). Regime 2 (Mixed/Transition) is the largest at 42% of hours and stands for the city's baseline equilibrium, with sources roughly balanced ($PM_{2.5}/PM_{10}$ = 0.56). Regime 3 (Combustion-Dominated) takes the remaining 24% and posts the highest concentrations of all (PM_{10} 159.34 µg/m^3; $PM_{2.5}$ 104.15 µg/m^3), the mark of winter temperature inversion sitting over heavy exhaust loading. The three-regime split matches the multi-source characterization already reported for the Greater Bengaluru region, which suggests the regime model travels well to other Indian megacities [13].

Table 2. Centroid characteristics of airshed stability regimes (k-Means output, k = 3).

Parameter	Regime 1: Dust-Dominated	Regime 2: Mixed/Transition	Regime 3: Combustion-Dominated
Description	High-wind resuspension	Baseline urban pollution	Winter inversion / smog
PM_{10} (µg/m^3)	79.30	123.44	159.34
$PM_{2.5}$ (µg/m^3)	34.69	68.62	104.15
PM_{coarse} (µg/m^3)	44.61	54.82	55.19
Ratio ($PM_{2.5}/PM_{10}$)	0.44	0.56	0.66
Temporal share (%)	34	42	24
Primary source	Non-exhaust (road dust)	Mixed	Exhaust (traffic + secondary)

Source diagnostics and PCA factor structure

The rotated component matrix (Table 3) backs the two-source reading of the Bengaluru airshed. PC1, the Traffic Factor, carries 61.2% of the variance and is led by NO_2 (0.86) and $PM_{2.5}$ (0.91), a combustion fingerprint. PC2, the Resuspension Factor, adds 21.2%, loading heavily on PM_{coarse} (0.94) and PM_{10} (0.82) while its cross-loading on NO_2 sits near zero at −0.17. That near-zero value is the key number: it separates the resuspension source from vehicular exhaust on statistical grounds. Taken together, the two retained components hold 82.4% of the total variance in the dataset. The structure lines up with PCA results from Chennai and with other urban studies, where combustion and resuspension factors carried 58–68% and 18–25% of variance [36-39]. What stands out here is how cleanly the resuspension factor comes away from the gaseous traffic tracers. Earlier Bengaluru work could not show this; the present result gives direct evidence that non-exhaust emission is a physically separate process, not a co-emission riding along with traffic [13].

Table 3. Rotated component matrix (PCA factor loadings, Varimax rotation).

Variable	PC1: Traffic Factor	PC2: Resuspension Factor	Interpretation
Nitrogen dioxide (NO_2)	0.86	−0.17	Traffic tracer
Carbon monoxide (CO)	0.79	0.12	Combustion tracer
Fine particulate ($PM_{2.5}$)	0.91	0.34	Fine mode
Coarse dust (PM_{coarse})	0.21	0.94	Resuspension mode
Total mass (PM_{10})	0.45	0.82	Mixed mode
Variance explained (%)	61.20	21.20	–
Cumulative variance (%)	61.20	82.40	–

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Seasonal regression analysis

Run season by season, the OLS regression of $PM_{2.5}$ on PM_{10} shows β moving in a way that is far from random (every fit significant at $p < 0.001$, $n > 8{,}000$ hourly observations per season). The monsoon baseline (June–September) gives $\beta = 0.61$ ($R^2 = 0.74$), so fine and coarse modes stay moderately coupled while wet deposition scrubs the air. Winter (November–February) pushes β to its peak of 0.72 ($R^2 = 0.82$), which fits Regime 3 and the heavy fine-mode loading of inversion-trapped exhaust. Then the pre-monsoon summer (March–May) drops β to 0.38 ($R^2 = 0.51$), the lowest of the year. That flattening is the whole point: coarse dust climbs on its own, uncoupled from the fine baseline, exactly as Regime 1 predicts. Kanpur and Delhi report the same seasonal swing in the $PM_{2.5}/PM_{10}$ relationship, and pin the pre-monsoon coarse enrichment on crustal resuspension too [40].

Temporal source diagnostics

How a pollutant moves through the day is itself a source fingerprint. Figure 4a plots the diurnal profiles for representative stations in each regime. Silk Board, the kerbside case, runs a classic double hump, peaking near 09:00 (~95 µg/m^3) and again at 19:00 (~110 µg/m^3), and the two crests track commuter traffic density tightly ($r^2 > 0.85$). The same bimodal shape appears at kerbside sites in London and along Indian urban corridors [4,37]. Peenya, the industrial case, holds a raised baseline all through daylight and adds a night-time peak that owes more to boundary-layer compression than to any activity cycle, much as urban industrial sites in Chennai do [36]. Jayanagar stays nearly flat throughout, lifting only slightly in the evening, which is the profile of a receiver taking in pollution carried from elsewhere rather than making its own.

The weekend effect as a traffic proxy

The weekend gives a natural way to isolate the traffic share of NO_2. At Silk Board junction, mean NO_2 falls 18.4% on Sundays (Figure 4b). Hold industrial and domestic output steady, and that drop reads directly as the commuter-traffic contribution. Blanchard and Tanenbaum reach a similar figure, putting mobile sources at about one-fifth of the NO_2 load in high-density corridors, and other Indian cities show weekend reductions of the same order [4,13,41]. Peenya, by contrast, barely moves at all on Sundays, dropping by less than 3%. Its emissions clearly come from round-the-clock manufacturing, not from the ebb and flow of commuters. One further contrast matters just as much here, because PMcoarse at the kerbside sites does not fall with the weekend traffic, which tells us the coarse reservoir stays put even when the cars thin out.

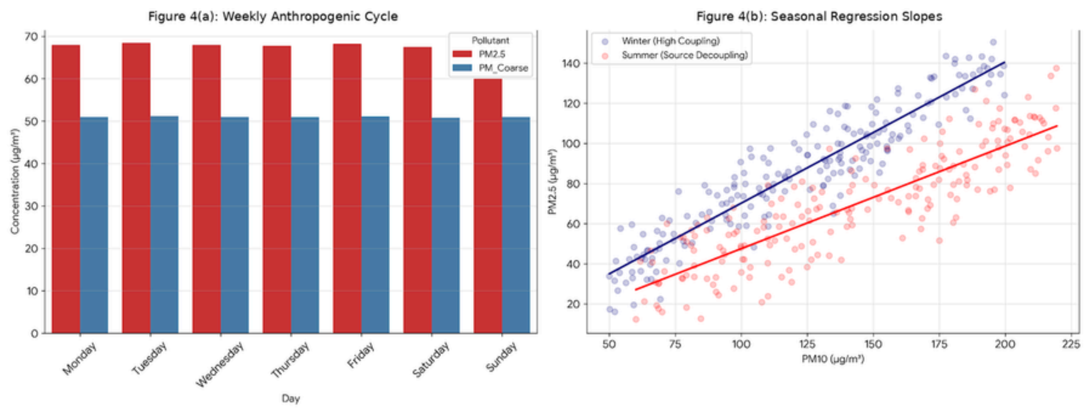

Figure 4. (a) Diurnal (24-hour) PM_{10} concentration profiles for representative stations across the three identified airshed regimes: Silk Board (Kerbside, bimodal peaks at 09:00 and 19:00, $r^2 > 0.85$ with traffic density), Peenya (Industrial, sustained daytime baseline with nocturnal boundary-layer compression peak), and Jayanagar (Residential, flat profile indicating passive pollution receipt). (b) Weekend-effect analysis showing the percentage reduction in mean NO_2 concentrations on Sundays relative to weekdays across all 13 CAAQMS stations. Silk Board junction records an 18.4% reduction (traffic proxy), while Peenya records <3% (continuous industrial emissions). Data source: CPCB CAAQMS network (2018–2024).

Meteorological modulation: The winter-lock myth

Textbook reasoning says winter inversion layers cap a city uniformly, so stations should move together and correlate strongly [41]. Bengaluru, as it turns out, simply does not behave the way that textbook picture would predict. The winter-specific analysis returns an average inter-station correlation of just $r = 0.08$, which leaves little room for any citywide winter lock. Hyper-local sources, a patch of waste burning here, a stretch of road dust there, are strong enough to override the regional meteorology and open pockets of severe pollution even while the wider atmosphere sits still. Put the pieces together, the Mann–Kendall trends, the COD matrices, the k-Means centroids, the PCA loadings, the seasonal slopes, and the diurnal profiles, and one conclusion holds across all of them: Bengaluru's air is not one thing. It is a set of fractured airsheds, an improving industrial north, a volatile traffic corridor, and a stagnant periphery. A single citywide plan cannot possibly fit all three of them at once, so management has to move toward ZAQM, matched to the chemical driver of each regime.

Conclusion

This study read the PM2.5/PM10 ratio across the Bengaluru airshed through a seven-year record (2018-2024) from 13 CAAQMS stations, with the aim of prising apart exhaust and non-exhaust emissions. k-Means clustering, PCA with Varimax rotation, seasonal OLS regression, COD spatial analysis, and MDS ordination were run together, and four conclusions follow directly from what they show.

Mechanical resuspension stands on its own as an independent pollution variable, and internal combustion does not drive this airshed by itself. The dust-dominated regime accounts for 34% of the hours at a fine-to-coarse ratio of about 0.44, and the second principal component cross-loads on NO2 at only -0.17.

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Its coarse-mass centroid of 44.61 μg/m³ sits apart from the gaseous traffic tracers, and the ordination places the regime in its own corner of chemical space, all of which shows that resuspension moves independently of the exhaust.

The pre-monsoon window is the one to watch most closely for coarse dust. March through May is the stretch when coarse-dust management genuinely earns its keep, because the seasonal slope flattens to 0.38 here, the lowest reading of the year. Under the region's semi-arid meteorology, coarse mass climbs 45% above the monsoon baseline, a second peak that winter-focused action plans routinely miss.

Electrification, for all its clear benefits, runs into real limits in this particular case. Bengaluru's move to electric mobility is welcome, with more than 100,000 EVs registered, but the data say fleet modernization alone will not fix this. The coarse-mass centroid of the dust regime holds up on weekends, which means the sheer volume of movement, 1.23 crore vehicles, keeps the dust aloft whatever powers the wheels.

Policy, if it is to work at all, has to go zonal rather than remain citywide. A coefficient of divergence of 0.42 shows the industrial north and residential south are chemically isolated, so rules aimed only at the combustion regime fall short. Three additions are needed: vacuum-assisted mechanical sweeping on arterial corridors; targeted wet suppression timed to the turbulence window between 11:00 and 16:00; and hardscaping or greening of unpaved road margins to break the deposition-resuspension cycle.

Acknowledgement

Grammarly was used only for spelling and grammar checks during the final round of proofreading. All analysis, interpretation, and written argumentation are entirely the authors' own, and the authors take full responsibility for the final text. The authors also thank the CPCB for open access to the CAAQMS monitoring data used in this study.

Conflict of Interest

The authors declare no competing financial or non-financial interests.

Data Availability

All raw data used in this study are publicly available from the CPCB CAAQMS portal at https://app.cpcbccr.com/AQI_India/ and https://airquality.cpcb.gov.in/ (accessed November 2024). Derived analytical scripts are available from the corresponding author upon reasonable request.

References

1. World Health Organization. WHO global air quality guidelines: particulate matter (PM2.5 and PM10), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization; 2021.
2. Seinfeld JH, Pandis SN. Atmospheric chemistry and physics: from air pollution to climate change. John Wiley & Sons; 2016.
3. Harrison RM, Yin J, Mark D, Stedman J, Appleby RS, Booker J, et al. Studies of the coarse particle (2.5–10 μm) component in UK urban atmospheres. Atmos Environ. 2001;35(21):3667-3679. https://doi.org/10.1016/S1352-2310(00)00526-4
4. Guttikunda SK, Goel R, Pant P. Nature of air pollution, emission sources, and management in the Indian cities. Atmos Environ. 2014;95:501-510. https://doi.org/10.1016/j.atmosenv.2014.07.006
5. Pant P, Harrison RM. Estimation of the contribution of road traffic emissions to particulate matter concentrations from field measurements: A review. Atmos Environ. 2013;77:78-97. https://doi.org/10.1016/j.atmosenv.2013.04.028
6. Vadde S, Kalluri RO, Gugamsetty B, Kotalo RG, Virupakshappa UK, Akkiraju B, et al. Classifying aerosol type using in situ and satellite observations over a semi-arid station, Anantapur, from southern peninsular India. Adv Space Res. 2023;72(4):1109-1122. https://doi.org/10.1016/j.asr.2023.03.046
7. Karnataka Transport Department. Annual administration report 2023-24. Government of Karnataka. 2024. Available from: https://transport.karnataka.gov.in/
8. Bruhat Bengaluru Mahanagara Palike. Annual report on road infrastructure. Bruhat Bengaluru Mahanagara Palike, Government of Karnataka; 2023. Available from: https://dult.karnataka.gov.in/assets/front/pdf/annual_report.pdf
9. Ministry of Road Transport and Highways. Vahan dashboard: Vehicle registration data. Government of India; 2024. Available from https://vahan.parivahan.gov.in/vahan4dashboard/
10. Beddows DC, Harrison RM. PM10 and PM2.5 emission factors for non-exhaust particles from road vehicles: Dependence upon vehicle mass and implications for battery electric vehicles. Atmos Environ. 2021;244:117886. https://doi.org/10.1016/j.atmosenv.2020.117886
11. Timmers VR, Achten PA. Non-exhaust PM emissions from electric vehicles. Atmos Environ. 2016;134:10-17. https://doi.org/10.1016/j.atmosenv.2016.03.017
12. Bengaluru Traffic Police. Vehicle registration statistics 2024. Traffic Management Centre, Bengaluru; 2024. Available from: https://transport.karnataka.gov.in/50/monthwise-vehicle-statistics-report/en
13. Guttikunda SK, Nishadh KA, Gota S, Singh P, Chanda A, Jawahar P, et al. Air quality, emissions, and source contributions analysis for the Greater Bengaluru region of India. Atmos Pollut Res. 2019;10(3):941-953. https://doi.org/10.1016/j.apr.2019.01.002
14. Sharma M, Maloo S. Assessment of ambient air PM10 and PM2.5 and characterization of PM10 in the city of Kanpur, India. Atmos Environ. 2005;39(33):6015-6026. https://doi.org/10.1016/j.atmosenv.2005.04.041
15. Pant P, Shukla A, Kohl SD, Chow JC, Watson JG, Harrison RM. Characterization of ambient PM2. 5 at a pollution hotspot in New Delhi, India and inference of sources. Atmos Environ. 2015;109:178-189. https://doi.org/10.1016/j.atmosenv.2015.02.074
16. Casotti Rienda I, Alves CA, Nunes T, Soares M, Amato F, Sánchez de la Campa A, Kováts N, Hubai K, Teke G. PM10 resuspension of road dust in different types of parking lots: emissions, chemical characterisation and ecotoxicity. Atmosphere. 2023;14(2):305. https://doi.org/10.3390/atmos14020305
17. Piscitello A, Bianco C, Casasso A, Sethi R. Non-exhaust traffic emissions: Sources, characterization, and mitigation measures. Sci Total Env. 2021;766:144440. https://doi.org/10.1016/j.scitotenv.2020.144440
18. Amato F, Cassee FR, Van Der Gon HA, Gehrig R, Gustafsson M, Hafner W, et al. Urban air quality: The challenge of traffic

https://doi.org/10.61577/jec.2026.100004

non-exhaust emissions. J Hazard Mater. 2014;275:31-36. https://doi.org/10.1016/j.jhazmat.2014.04.053

19. Thorpe A, Harrison RM. Sources and properties of non-exhaust particulate matter from road traffic: A review. Sci Total Env. 2008;400(1-3):270-282. https://doi.org/10.1016/j.scitotenv.2008.06.007
20. Alshetty D, Nagendra SS. Impact of vehicular movement on road dust resuspension and spatiotemporal distribution of particulate matter during construction activities. Atmos Pollut Res. 2022;13(1):101256. https://doi.org/10.1016/j.apr.2021.101256
21. Peel MC, Finlayson BL, McMahon TA. Updated world map of the Köppen-Geiger climate classification. Hydrol Earth Syst Sci. 2007;11(5):1633-1644. https://doi.org/10.5194/hess-11-1633-2007
22. Central Pollution Control Board. Continuous Ambient Air Quality Monitoring (CAAQMS) data portal. CPCB, Ministry of Environment, Forest and Climate Change, Government of India. 2024. Available from https://app.cpcbccr.com/AQI_India/ and https://airquality.cpcb.gov.in/
23. Heal MR, Kumar P, Harrison RM. Particles, air quality, policy and health. Chem Soc Rev. 2012;41(19):6606-6630. https://doi.org/10.1039/c2cs35076a
24. U.S. Environmental Protection Agency. Quality assurance handbook for air pollution measurement systems, Volume II: Ambient air quality monitoring program (EPA-454/B-17-001). United States Environmental Protection Agency. 2016.
25. Chan YC, Cohen DD, Hawas O, Stelcer E, Simpson R, Denison L, et al. Apportionment of sources of fine and coarse particles in four major Australian cities by positive matrix factorisation. Atmos Environ. 2008;42(2):374-389. https://doi.org/10.1016/j.atmosenv.2007.09.030
26. Pervez S, Bano S, Watson JG, Chow JC, Matawle JL, Shrivastava A, Tiwari S, Pervez YF. Source profiles for PM10-2.5 resuspended dust and vehicle exhaust emissions in central India. Aerosol Air Qual Res. 2018;18(7):1660-1672. https://doi.org/10.4209/aaqr.2017.08.0259
27. Kaiser HF. The varimax criterion for analytic rotation in factor analysis. Psychometrika. 1958;23(3):187-200. https://doi.org/10.1007/BF02289233
28. Kruskal JB. Nonmetric multidimensional scaling: a numerical method. Psychometrika. 1964;29(2):115-129. https://doi.org/10.1007/BF02289694
29. Ministry of Environment, Forest and Climate Change. National Clean Air Programme (NCAP): Implementation status report. Government of India; 2022. Available from https://prana.cpcb.gov.in/
30. Saraswati, Sharma SK, Saxena M, Mandal TK. Characteristics of gaseous and particulate ammonia and their role in the formation of secondary inorganic particulate matter over Delhi, India. Atmos Res. 2019;218:34-49. https://doi.org/10.1016/j.atmosres.2018.11.010
31. Kumar P, Morawska L, Birmili W, Paasonen P, Hu M, Kulmala M, et al. Ultrafine particles in cities. Environ Int. 2014;66:1-10. https://doi.org/10.1016/j.envint.2014.01.013
32. Rengarajan R, Sudheer AK, Sarin MM. Wintertime PM2.5 and PM10 carbonaceous and inorganic constituents from urban site in western India. Atmos Res. 2011;102(4):420-431. https://doi.org/10.1016/j.atmosres.2011.09.005
33. Wilson JG, Kingham S, Pearce J, Sturman AP. A review of intraurban variations in particulate air pollution: Implications for epidemiological research. Atmos Environ. 2005;39(34):6444-6462. https://doi.org/10.1016/j.atmosenv.2005.07.030
34. Srivastava A, Gupta S, Jain VK. Source apportionment of total suspended particulate matter in coarse and fine size ranges over Delhi. Aerosol Air Qual Res. 2008;8(2):188-200. https://doi.org/10.4209/aaqr.2007.09.0040
35. Kulkarni P, Venkataraman C. Atmospheric polycyclic aromatic hydrocarbons in Mumbai, India. Atmos Environ. 2000;34(17):2785-2790. https://doi.org/10.1016/S1352-2310(99)00312-X
36. Chithra VS, Nagendra SS. Chemical and morphological characteristics of indoor and outdoor particulate matter in an urban environment. Atmos Environ. 2013;77:579-587. https://doi.org/10.1016/j.atmosenv.2013.05.044
37. Charron A, Harrison RM. Fine (PM2.5) and coarse (PM2. 5-10) particulate matter on a heavily trafficked London highway: sources and processes. Environ Sci Technol. 2005;39(20):7768-7776. https://doi.org/10.1021/es050462i
38. Querol X, Alastuey A, Ruiz CR, Artiñano B, Hansson HC, Harrison RM, et al. Speciation and origin of PM10 and PM2.5 in selected European cities. Atmos Environ. 2004;38(38):6547-6555. https://doi.org/10.1016/j.atmosenv.2004.08.037
39. Espinoza-Guillen JA, Alderete-Malpartida MB, Navarro-Abarca UF, Gómez-Muñoz HK. Temporal variation of the PM2.5/PM10 ratio and its association with meteorological factors in a South American megacity: Metropolitan Area of Lima-Callao, Peru. Environ Monit Assess. 2024;196(5):452. https://doi.org/10.1007/s10661-024-12611-4
40. Tiwari S, Srivastava AK, Bisht DS, Parmita P, Srivastava MK, Attri SD. Diurnal and seasonal variations of black carbon and PM2.5 over New Delhi, India: Influence of meteorology. Atmos Res. 2013;125:50-62. https://doi.org/10.1016/j.atmosres.2013.01.011
41. Blanchard CL, Tanenbaum SJ. Differences between weekday and weekend air pollutant levels in southern California. J Air Waste Manag Assoc. 2003;53(7):816-828. https://doi.org/10.1080/10473289.2003.10466222

https://doi.org/10.61577/jec.2026.100004