



A Multi-Factorial Mechanistic Framework for the Severe Winter Air Pollution Episodes in Delhi: Interactions Between Local Baseline Load, Regional Forcing, and Urban Entrapment

Author: ADARSH KUMAR AND PRABHAT KUMAR

Affiliation: Institution: Balaji publications,
Muzaffar Nagar, 251001

Abstract: Delhi's recurrent winter air pollution crises reflect a complex interaction among chronic local emissions, episodic regional atmospheric dynamics, and unfavorable urban morphology. This study integrates data from source apportionment analyses, atmospheric transport modeling, and urban fluid dynamics to construct a mechanistic framework explaining severe particulate matter (PM) episodes. Persistent local sources, especially fugitive dust from construction and demolition (C&D) activities and vehicular emissions, sustain a high year-round PM baseline. Crop residue burning (CRB) in surrounding states acts as a thermal accelerator, generating temperature–pressure gradients that promote pollutant transport into Delhi. Finally, the city's dense urban fabric and low winter planetary boundary layer (PBL) inhibit vertical dispersion, amplifying pollutant accumulation. The findings emphasize that single-season or single-source interventions are inadequate. Sustainable mitigation requires a year-round, multi-sectoral approach targeting emission reduction, meteorological modulation, and ventilation-focused urban design.

Keywords: Air pollution, Delhi, PM_{2.5}, Crop residue burning, Urban morphology, Thermal forcing, Source apportionment

I. INTRODUCTION

Delhi is consistently ranked among the most polluted capital cities in the world, where winter particulate matter (PM_{2.5}) concentrations often exceed 250 µg/m³ and frequently reach levels above 400 µg/m³, classified as “Hazardous”. While such episodes are often attributed chiefly to crop residue burning (CRB) in neighboring states, multiple studies indicate substantial particulate contributions from local and regional sources even outside the CRB season (Sharma et al., 2016).

This study proposes a systemic interpretation of Delhi's winter air quality crisis through three interacting mechanisms:

1. Chronic baseline accumulation: Persistent local emissions establish a year-round high PM reservoir.
2. Regional meteorological forcing: Episodic CRB introduces strong thermal gradients that drive pollutant transport into Delhi.
3. Urban trapping: Dense urban morphology limits atmospheric ventilation, aggravating accumulation during winter inversions.

The goal is to integrate quantitative evidence across multiple disciplines to explain Delhi's recurrent smog as a systemic function rather than an episodic anomaly and to derive practical policy directions.

II. METHODOLOGY

A comprehensive literature synthesis and data review were conducted using studies published between 2016 and 2025 that examined air quality dynamics in Delhi and the National Capital Region (NCR). The analysis incorporated findings from official technical reports (CPCB, DPCC, NEERI) and peer-reviewed publications.

2.1 Source Apportionment: Local Baseline Load

Official source apportionment reports and crustal composition analyses were used to quantify contributions from vehicular emissions, C&D dust, and secondary aerosols. Seasonal trends of PM₁₀ and PM_{2.5} were compared to identify the persistence of Delhi's background particulate load. Particular attention was given to the crustal (Si, Fe, Al) and soluble ion fractions that signify mechanical and combustion sources.

2.2 Regional Atmospheric Forcing: CRB and Meteorological Transport

Meteorological model outputs, fire count data, and backward trajectory simulations (HYSPLIT) were analyzed to understand the influence of CRB events. Studies in Science of the Total Environment and Environmental Pollution were synthesized to characterize the "thermal pushing" mechanism, where large-scale heat release from biomass burning alters regional pressure and wind dynamics, channeling pollutants toward Delhi.

2.3 Urban Micro-Meteorology: Morphological Entrapment

Urban-scale airflow and pollutant dispersion characteristics were examined using Computational Fluid Dynamics (CFD) and numerical simulations from Building and Environment (2021) and MDPI (2022). Key parameters analyzed included building height-to-street-width ratio (H/W), turbulent kinetic energy (TKE) distribution, and the effect of planetary boundary layer suppression under winter inversion conditions.

III. RESULTS AND DISCUSSION

3.1 Chronic Local Emissions and Baseline PM Load

Local sources maintain an elevated particulate reservoir throughout the year, providing a substrate for intensified winter episodes.

Construction and Road Dust

Fugitive dust from C&D sites and road surfaces dominates coarse particulate matter. CEEW (2025) measured average PM₁₀ concentrations of $749 \pm 1013 \mu\text{g}/\text{m}^3$ in high-activity construction areas, far exceeding the NAAQS limit of $100 \mu\text{g}/\text{m}^3$. This primary load enhances secondary condensation and coagulation during periods of atmospheric stagnation.

Vehicular and Secondary Aerosols

Vehicular exhaust and industrial combustion contribute fine-mode particles and chemical precursors that form secondary sulfates and nitrates. Such aerosols account for approximately 26–28% of winter PM_{2.5} mass (Sharma et al., 2016), influencing both optical density and toxicity.

3.2 Regional Forcing and the Thermal Pushing Mechanism

Direct emissions from CRB typically contribute 9–18% of PM_{2.5} mass in Delhi during October–November (STOTEN, 2024). However, their meteorological influence is far greater:

- Thermal gradients: Extensive heat release creates regional pressure differentials along the Indo-Gangetic Plain, promoting low-level convergence.
- Advection into Delhi: Under low-wind, shallow PBL conditions, these dynamics transport pollutant-laden air masses into the Delhi basin, where they become trapped (Environmental Pollution, 2023).

Thus, CRB functions as both a direct emission and a dynamic regional transport driver.

3.3 Urban Morphology and Entrapment Effects Conclusion and Policy Recommendations

Delhi's complex urban structure significantly restricts pollutant ventilation.

- Street canyon effects: CFD analyses show that high H/W ratios suppress horizontal exchange, producing isolated recirculation zones and limiting vertical dispersion (Building and Environment, 2021).
- Reduced TKE: High-rise clustering reduces TKE at pedestrian levels, especially under low wind speeds, increasing pollutant residence time (MDPI, 2022).
- Inversion-induced confinement: During winter, the PBL often descends below 300 meters, functioning as an effective lid. Aerosol growth processes—including condensation and coagulation—become dominant, magnifying PM_{2.5} mass and reducing visibility (Şahin et al., 2022).

Together, these morphological and meteorological effects transform an elevated particulate background into hazardous air quality events.

IV. CONCLUSION AND POLICY RECOMMENDATIONS

Delhi's winter smog is a manifestation of systemic particulate load mismanagement, compounded by meteorological reinforcement and urban ventilation failure. Effective mitigation must address each of these interacting drivers.

1. Lower baseline emissions: Implement continuous dust control measures with real time compliance tracking at C&D sites, modernize vehicle fleets, and promote clean fuel transition to reduce primary and secondary particle sources.
2. Eliminate thermal forcing: Support CRB elimination through agricultural residue utilization technologies, subsidized biomass collection, and incentive-based management systems.
3. Enhance ventilation design: Institutionalize CFD-based air circulation assessments in master planning to preserve air corridors and limit dense vertical clustering that inhibits dispersion.

Delhi's air quality crisis demands a structural, year-round approach integrating emission regulation, agricultural reform, and urban design planning.

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