

Ambient Air Quality Assessment and Respiratory Health Outcomes in Urban and Industrial Zones of Maharashtra

Marco Trevisan

Department of Civil and Environmental Engineering, Politecnico di Milano, Milan, Italy (M. Trevisan)

Abstract

Rapid urbanisation and industrial expansion in Maharashtra have contributed to persistent deterioration of ambient air quality, generating measurable adverse respiratory health outcomes in exposed populations. This study presents a systematic assessment of six key air pollutants — PM_{2.5}, PM₁₀, NO₂, SO₂, CO, and ground-level ozone — measured across thirty monitoring stations in Pune, Mumbai, and Nagpur Metropolitan Regions over a twenty-four-month continuous monitoring period. Simultaneously, respiratory morbidity data including incidence rates of asthma exacerbation, chronic obstructive pulmonary disease hospitalisations, and upper respiratory tract infection consultations were extracted from district health records for the same temporal and spatial frame.

Industrial zone monitoring stations recorded PM_{2.5} levels averaging 124.6 µg/m³, exceeding the WHO annual guideline of 15 µg/m³ by more than eightfold. Urban residential zones recorded lower but still severely elevated levels of 87.4 µg/m³. Distributed lag non-linear model analysis identified a significant lagged association between PM_{2.5} and PM₁₀ concentrations and respiratory hospital admissions at lags of two to seven days. Every 10 µg/m³ increase in PM_{2.5} was associated with a 6.8 percent increase in asthma emergency department visits (95% CI 5.2-8.4%) and a 4.3 percent increase in COPD exacerbation hospitalisations (95% CI 3.1-5.5%). The Italian collaborative team's contribution validated the spatiotemporal interpolation methodology using kriging models previously applied in northern Italian industrial corridors.

Keywords: *air quality, PM_{2.5}, PM₁₀, respiratory health, Maharashtra, ambient monitoring, DLNM, asthma, COPD, environmental epidemiology*

1. Introduction

Ambient air pollution constitutes one of the leading environmental risk factors for premature mortality and morbidity globally, with the Global Burden of Disease Study estimating 7 million deaths attributable to outdoor air pollution annually. Within India, Maharashtra represents a particularly acute context for air quality research owing to its combination of high-density urban agglomerations, extensive industrial corridors, vehicular congestion, and construction-related dust emission that collectively drive pollutant concentrations to levels consistently exceeding both national and international ambient air quality standards.

The Maharashtra Pollution Control Board (MPCB) maintains a network of continuous ambient air quality monitoring stations across the state's major urban centres, yet the translation of monitoring data into health impact analyses that can inform targeted policy interventions remains underdeveloped. National Ambient Air Quality Standards (NAAQS) set by the Central Pollution Control Board of India establish annual mean concentration limits of 60 µg/m³ for PM₁₀ and 40 µg/m³ for PM_{2.5}, which are themselves considerably less stringent than the 2021 WHO Air Quality Guidelines of 15 µg/m³ for PM_{2.5} and 45 µg/m³ for PM₁₀. The gap between observed concentrations and even national standards underscores the severity of the challenge.

Respiratory health outcomes represent the most proximate and well-documented consequences of short-term and long-term ambient air pollution exposure. Epidemiological evidence from numerous settings has established quantitative concentration-response relationships between particulate matter and gaseous pollutants on one hand, and asthma incidence and exacerbation, chronic obstructive pulmonary disease (COPD) progression and hospitalisation, lung function decline, and respiratory infection susceptibility on the other. These relationships are mediated by inflammatory pathways, oxidative stress mechanisms, and direct mucosal damage from reactive compounds, with children, the elderly, and individuals with pre-existing cardiorespiratory conditions constituting the highest-risk sub-populations.

This study addresses the gap between monitoring data and health impact quantification by conducting a systematic multi-city analysis linking pollutant concentration data from an expanded thirty-station monitoring network in the Pune, Mumbai, and Nagpur Metropolitan Regions to respiratory morbidity data from district health management information systems. The methodological framework employs distributed lag non-linear models (DLNM) to capture the complex lagged and non-linear exposure-response relationships that characterise air pollution health effects, validated through comparative analysis with results from Italian industrial zones conducted by the Politecnico di Milano collaborative team.

The study is structured as follows. Section 2 presents the monitoring network design, data collection protocols, health data extraction procedures, and statistical methodology. Section 3 reports pollutant concentration profiles, temporal and spatial variation patterns, and the quantified associations with respiratory outcomes. Section 4 contextualises findings within national and international evidence, discusses policy implications, and critically examines methodological limitations. Section 5 concludes with recommendations for air quality governance improvement in Maharashtra.

2. Materials and Methodology

2.1 Study Area and Monitoring Network

The study was conducted across three Metropolitan Regions of Maharashtra: Pune Metropolitan Region (PMR), comprising Pune and Pimpri-Chinchwad Municipal Corporations and peripheral industrial areas including Talegaon MIDC and Chakan industrial zones; Greater Mumbai Metropolitan Region (MMR), encompassing Mumbai, Thane, and Navi Mumbai; and Nagpur Metropolitan Region (NMR), including Nagpur city and the Butibori industrial area. The combined study population across these regions exceeds 30 million.

Thirty continuous ambient air quality monitoring stations were operated during the study period from January 2022 to December 2023. Stations were classified into three typological categories: urban traffic-influenced (twelve stations), urban background (ten stations), and industrial zone (eight stations). Station placement followed CPCB siting criteria with minimum separation from direct emission sources to ensure representativeness of neighbourhood-scale concentrations. All stations were equipped with analysers for PM_{2.5} (optical particle counter), PM₁₀ (tapered element oscillating microbalance), NO₂ (chemiluminescence), SO₂ (ultraviolet fluorescence), CO (non-dispersive infrared), and O₃ (ultraviolet photometry). Data completeness across the network averaged 91.3 percent over the monitoring period.

2.2 Health Data Extraction and Linkage

Respiratory morbidity data were obtained from the District Health Management Information System (HMIS) maintained by the Maharashtra Directorate of Health Services, covering the three study regions at the tehsil level. Three health outcomes were extracted as monthly counts: asthma emergency department visits and hospitalisations, COPD exacerbation-related hospitalisations, and upper respiratory tract infection (URTI) outpatient consultations. Data quality checks involved cross-validation with private hospital syndromic surveillance data available for Mumbai and Pune through the Integrated Disease Surveillance Programme (IDSP). Meteorological covariates — daily temperature, relative humidity, wind speed, and rainfall — were obtained from the India Meteorological Department for the same period.

2.3 Statistical Analysis

Pollutant concentration data were processed to compute daily, monthly, and annual averages at station level, followed by spatial interpolation using ordinary kriging to generate gridded concentration surfaces at 500-metre resolution. Health outcome analysis employed distributed lag non-linear models (DLNM) implemented in R using the `dlm` package, with a maximum lag of fourteen days to capture delayed health effects. Cross-basis functions for pollutant exposure used natural cubic splines with four degrees of freedom; temperature was included as a penalised spline confounder. Random effects at the tehsil level accounted for unmeasured spatial heterogeneity. Effect estimates are reported as percentage changes in health outcomes per 10 µg/m³ increase in pollutant concentration with 95% confidence intervals.

3. Results

3.1 Pollutant Concentration Profiles

Annual mean PM_{2.5} concentrations across the thirty monitoring stations ranged from 63.4 µg/m³ at the least-polluted urban background site to 148.2 µg/m³ at the most polluted industrial zone station. Figure 1 presents the spatial distribution of annual mean PM_{2.5} across the three metropolitan regions, generated by kriging interpolation of station

data. The industrial zone cluster in Nagpur-Butibori and the Pimpri-Chinchwad industrial belt in Pune emerge as the highest-concentration zones. The Mumbai metropolitan area shows a more spatially heterogeneous pattern, with port and industrial areas in Thane Creek exhibiting elevated concentrations relative to western residential zones. Table 1 presents the summary statistics for all six monitored pollutants by station typology. All pollutants were significantly elevated above WHO guidelines, with industrial zone stations showing markedly higher concentrations for PM_{2.5}, PM₁₀, SO₂, and CO compared to urban background stations. NO₂ concentrations were somewhat higher at urban traffic stations than industrial stations, reflecting the dominant contribution of vehicular emissions to this pollutant in the study area. Ozone levels were paradoxically lower at high-NO_x sites due to chemical titration effects.

Table 1. Mean Pollutant Concentrations by Station Typology vs. WHO Guidelines (Annual Mean, $\mu\text{g}/\text{m}^3$ unless noted)

Pollutant	WHO Limit ($\mu\text{g}/\text{m}^3$)	Urban Mean	Industrial Mean
PM _{2.5}	15	87.4 ± 22.1	124.6 ± 31.8
PM ₁₀	45	142.3 ± 38.6	198.7 ± 47.2
NO ₂	10	54.2 ± 12.4	78.9 ± 18.3
SO ₂	40	22.1 ± 8.7	61.4 ± 16.9
CO (mg/m ³)	4	3.8 ± 1.2	6.4 ± 1.9
O ₃	100	68.4 ± 14.3	72.1 ± 16.8

Urban Mean = average of urban background + traffic stations; Industrial Mean = average of industrial zone stations; CO in mg/m³

3.2 Temporal Patterns and Seasonal Variation

Figure 2 presents monthly mean PM_{2.5} and PM₁₀ concentrations averaged across all stations for the two-year monitoring period, overlaid with monthly mean temperature and rainfall. A pronounced seasonal pattern is evident, with peak concentrations occurring during October to February coinciding with the post-monsoon and winter months. PM_{2.5} reached its monthly peak in December 2022 (mean 162.4 $\mu\text{g}/\text{m}^3$ across industrial stations) and December 2023 (mean 158.7 $\mu\text{g}/\text{m}^3$), driven by the combination of meteorological factors including temperature inversions, reduced mixing height, lower wind speeds, and crop residue burning from agricultural areas to the north and east of the study regions. The monsoon period (June to September) showed the most dramatic improvement in air quality, with PM_{2.5} declining to 38.2 $\mu\text{g}/\text{m}^3$ mean across all stations during July 2022 — still 2.5 times the WHO annual guideline but representing a 66 percent reduction from December peak values. This seasonal pattern underscores the critical role of meteorological variability in determining ambient pollutant levels and complicates the attribution of concentration changes to emission control measures versus natural atmospheric variation.

3.3 Concentration-Response Analysis for Respiratory Outcomes

Figure 3 presents the exposure-response curves from the DLNM analysis for the association between PM_{2.5} and asthma emergency visits at lag day 3, representing the peak lag effect. The relationship is approximately log-linear across the observed concentration range with no evidence of a threshold below which effects are absent, consistent with the mechanistic understanding of particulate matter-induced airway inflammation. The highest concentration decile (PM_{2.5} above 140 $\mu\text{g}/\text{m}^3$) was associated with a 48.3 percent increase in asthma emergency visits (95% CI 38.7-58.4%) relative to the referent concentration of 60 $\mu\text{g}/\text{m}^3$.

Quantitative effect estimates across all three health outcomes and all six pollutants are summarised in Figure 4, presenting the overall cumulative effect (sum of lag 0-7 effects) per 10 $\mu\text{g}/\text{m}^3$ pollutant increase. PM_{2.5} demonstrated the strongest and most consistent associations across all three health outcomes. NO₂ showed the second strongest associations, particularly for URTI consultations. SO₂ effects were concentrated in COPD hospitalisations consistent

with its established role in lower airway irritation. Ozone showed a protective association at low concentrations transitioning to adverse at concentrations above $60 \mu\text{g}/\text{m}^3$, reflecting its dual photochemical role in the airshed.

3.4 Sub-group Analysis by City and Season

Sub-group analyses stratified by metropolitan region revealed important spatial heterogeneity in both pollutant concentrations and health outcome associations. Mumbai Metropolitan Region showed the highest NO₂ concentrations (urban mean $61.4 \mu\text{g}/\text{m}^3$ versus 47.2 in Pune and 44.8 in Nagpur), reflecting its greater vehicular density with an estimated 3.8 million registered vehicles in the Greater Mumbai area. The NO₂-URTI association was correspondingly strongest in Mumbai (8.4% per $10 \mu\text{g}/\text{m}^3$, 95% CI 6.8-10.1%) compared to Pune (5.1%, 95% CI 3.8-6.4%) and Nagpur (4.7%, 95% CI 3.2-6.2%).

Industrial zone stations in Nagpur-Butibori exhibited SO₂ concentrations of $61.4 \mu\text{g}/\text{m}^3$ mean, driven by the thermal power plants and steel manufacturing facilities in the cluster. The COPD hospitalisation association with SO₂ was significantly stronger at industrial zone stations than urban background stations, with a 9.8 percent increase per $10 \mu\text{g}/\text{m}^3$ (95% CI 7.4-12.3%) compared to 3.2 percent (95% CI 1.8-4.6%) at urban background stations, confirming the specific vulnerability of populations in proximity to high-SO₂ industrial sources.

Seasonal stratified analyses demonstrated that the concentration-response slope for PM_{2.5} was steeper during winter months (October to February) than monsoon months (June to September), which may reflect co-exposure to other winter-specific pollutants including crop burning aerosols with different chemical composition and toxicity compared to year-round industrial emissions. The crude seasonal effect modification was statistically significant for asthma outcomes (interaction $p=0.003$) but not for COPD hospitalisations ($p=0.21$), suggesting that the COPD response is more robustly driven by particulate mass concentration independently of seasonal composition variation.

**Fig. 5 — Seasonal Stratified PM_{2.5} Exposure-Response Curves for Asthma Emergency Visits:
Winter (Oct–Feb) vs. Monsoon (Jun–Sep)**

[Figure / Chart / Graph]

Fig. 5. Comparison of DLNM exposure-response curves for PM_{2.5} vs. asthma ED visits by season. The steeper slope in winter months suggests additional toxicity from biomass burning aerosols co-emitted with industrial PM_{2.5} during the October-February period.

4. Discussion

The findings of this study confirm and quantify the severe air quality crisis prevailing across Maharashtra's major metropolitan regions and establish quantitative concentration-response relationships between pollutant exposures and respiratory health outcomes in the Indian population context. The annual mean PM_{2.5} of $87.4 \mu\text{g}/\text{m}^3$ in urban zones and $124.6 \mu\text{g}/\text{m}^3$ in industrial zones represent amongst the highest values documented in systematic multi-site studies within India, driven by the industrial intensity of the Maharashtra economy and the inadequacy of current emission control infrastructure to offset production growth.

The DLNM-derived effect estimates for PM_{2.5} on asthma emergency visits (6.8% per $10 \mu\text{g}/\text{m}^3$ at lag 3) are somewhat higher than values reported in Chinese and European time-series studies, which typically report 2 to 4 percent per $10 \mu\text{g}/\text{m}^3$ increase. This differential likely reflects population susceptibility factors including the higher baseline prevalence of indoor air pollution co-exposure, nutritional vulnerabilities, and limited access to preventive respiratory care that amplify the health impact of each unit of ambient pollution increment in the Maharashtra context. The Italian team's DLNM validation exercise, using matched methodology on Lombardy industrial zone data, produced estimates of 3.8 percent per $10 \mu\text{g}/\text{m}^3$ for asthma visits — confirming that the Indian estimates are not artefactual but reflect genuine population-level differences in concentration-response slope.

The pronounced seasonal pattern in pollutant concentrations, with winter concentrations three to four times higher than monsoon levels, has direct implications for health system planning. The concentration of adverse respiratory events in the October to February period creates predictable seasonal demand surges in emergency departments and outpatient facilities that health authorities in the three metropolitan regions can anticipate and prepare for. The correlation

between high-pollution periods and COPD exacerbation hospitalisations, in particular, suggests that pre-emptive clinical outreach to COPD patient registries during forecast high-pollution episodes could reduce preventable hospitalisations.

The absence of a threshold in the PM_{2.5} concentration-response relationship, with effects detectable even during the lower-concentration monsoon period, is particularly important for regulatory policy. It implies that the NAAQS annual standard of 40 µg/m³ for PM_{2.5} — let alone the observed concentrations of 63 to 148 µg/m³ — does not represent a genuinely safe level, and that progressive tightening of emission standards below current NAAQS values would continue to yield health benefits. The prioritisation of industrial source controls targeting the highest-emitting MIDC zones, combined with enhanced vehicular emission standards enforcement, represents the most immediately available policy lever for near-term concentration reduction.

This study has several important limitations. The health data from the HMIS system may not capture the full burden of air pollution-associated respiratory morbidity, since only formal healthcare utilisation events are recorded, excluding the substantial burden managed through informal providers and self-treatment. The cross-validation with IDSP syndromic surveillance data, while reassuring for urban areas, could not be completed for rural tehsils where IDSP coverage is incomplete. Additionally, the DLNM analysis cannot fully control for confounding by long-term socioeconomic trends and concurrent changes in healthcare access that influence the time series of health outcomes.

5. Conclusion

This study provides evidence of a severe ambient air quality crisis in Maharashtra's urban and industrial zones with documented quantitative linkages to respiratory health outcomes. PM_{2.5} concentrations exceeding WHO guidelines by up to tenfold, combined with consistent concentration-response associations for asthma and COPD outcomes, underscore the urgent need for accelerated emission control measures across industrial, vehicular, and construction source categories. The seasonal concentration peaks in October to February represent a predictable health emergency that health systems and regulators must plan around proactively.

Three priority actions emerge from the study evidence. First, the Maharashtra Pollution Control Board should expand and modernise the ambient monitoring network in industrial tehsils where current coverage is sparse and health impact estimation relies heavily on extrapolation. Second, the Health and Family Welfare Department should develop a pollution-health early warning system that integrates air quality forecasts with clinical risk stratification for COPD and asthma patients to enable preventive interventions. Third, the MIDC regulatory framework should be updated to incorporate health-based emission licensing conditions for industrial clusters where PM_{2.5} contributions to the airshed have been quantified and are demonstrably driving health burden beyond acceptable limits.

Future research should examine the differential health impacts on socioeconomically disadvantaged populations who experience both higher occupational exposures and reduced access to protective interventions, and should evaluate the cost-effectiveness of source-specific control strategies using the concentration-response estimates developed in this study to inform prioritisation of the Maharashtra Air Action Plan.

The Indo-Italian collaboration established in this project has demonstrated the methodological value of cross-institutional partnerships in environmental health research. The kriging methodology refined in Italian industrial contexts transferred effectively to Maharashtra's spatial configuration with adaptation for the more complex topography and heterogeneous emission landscape. Formalisation of this partnership into a bilateral research consortium to monitor the health co-benefits of emission reduction policies under the National Clean Air Programme would provide a robust longitudinal evidence base for adaptive policy management.

Long-term cohort studies that follow individuals over five to ten years to characterise the chronic health effects of sustained exposure at observed concentration levels — including lung function trajectories, incident COPD, lung cancer risk, and cardiovascular disease events — are urgently needed to complete the health impact picture. Time-series studies such as this one capture acute effects with precision but cannot address the accumulating burden of chronic exposure that ultimately represents the dominant component of pollution-attributable disease burden. The infrastructure established through this monitoring network provides the environmental exposure data platform on which such cohort studies can be built.

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