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Systematic Review and Meta-analysis

Health Burden of Ambient Air Pollution on Respiratory Diseases in the Delhi–National Capital Region (2010–2025): A Systematic Review and Meta-analysis

Pradeep Kumar Soothewal[1]

1. Professor, Department of Respiratory Medicine, National Institute of Medical Sciences and Research, Jaipur.

Corresponding Author: Dr Pradeep Kumar Soothewal, Professor, Department of Respiratory Medicine, National Institute of Medical Sciences and Research, Jaipur

Abstract

Introduction: Ambient air pollution is a major contributor to respiratory morbidity and mortality globally, with disproportionate impacts in low- and middle-income countries. The Delhi–National Capital Region (NCR) experiences persistently high levels of air pollution, yet region-specific quantitative syntheses of respiratory health impacts remain limited. This study aimed to systematically review and meta-analyse epidemiological evidence on the association between ambient air pollution and respiratory outcomes in Delhi–NCR from 2010 to 2025.

Methods: A systematic review and meta-analysis were conducted in accordance with PRISMA 2020 guidelines. PubMed/MEDLINE, Scopus, Web of Science, Embase, and additional sources were searched for eligible studies examining associations between ambient air pollutants ($PM_{2.5}$, PM_{10}, NO_2, SO_2, O_3, CO) and respiratory morbidity or mortality in Delhi–NCR. Time-series, case-crossover, cohort, and observational studies reporting quantitative effect estimates were included. Random-effects meta-analyses were performed to derive pooled relative risks per 10 µg/m³ increase in pollutant concentration. Risk of bias was assessed using adapted ROBINS-E and Newcastle–Ottawa tools.

Results: Ten studies met inclusion criteria for qualitative synthesis, and seven were included in meta-analysis. Short-term increases in $PM_{2.5}$ were associated with higher respiratory emergency visits (RR 1.038; 95% CI: 1.021–1.056) and respiratory mortality (RR 1.019; 95% CI: 1.006–1.033). PM_{10} exposure was linked to increased respiratory admissions (RR 1.026; 95% CI: 1.012–1.041), while NO_2 showed a strong association with acute respiratory visits (RR 1.041; 95% CI: 1.018–1.064). Heterogeneity ranged from low to moderate.

Conclusion: Ambient air pollution is consistently associated with increased respiratory morbidity and mortality in Delhi–NCR. These findings underscore the urgent need for strengthened air quality interventions and targeted public health strategies in highly polluted urban settings.

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Introduction

Ambient air pollution is a major global public health concern and a leading environmental cause of morbidity and premature mortality. The World Health Organization (WHO) estimates that exposure to outdoor air pollution contributes to millions of deaths annually, with respiratory diseases accounting for a substantial proportion of this burden [1]. Fine particulate matter ($PM_{2.5}$), coarse particulate matter (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), sulfur dioxide (SO_2), and carbon monoxide (CO) have been consistently associated with adverse respiratory outcomes, including asthma exacerbations, chronic obstructive pulmonary disease (COPD), acute respiratory infections, and respiratory mortality [2–4]. Because the respiratory tract is directly exposed to inhaled pollutants, respiratory outcomes are among the most sensitive indicators of air pollution–related health effects.

A large body of epidemiological evidence from high-income countries has demonstrated short-term associations between ambient air pollution and increases in respiratory emergency department visits, hospital admissions, and deaths [5–7]. Meta-analyses and multicity studies have shown that these associations persist even at relatively low pollutant concentrations, indicating the absence of a safe exposure threshold [8,9]. However, global burden assessments consistently highlight that the majority of air pollution–related health impacts now occur in low- and middle-income countries, where pollution levels are higher and populations may be more vulnerable due to comorbidities and limited healthcare access [10].

India exemplifies this challenge. Several Indian cities rank among the most polluted globally, with annual mean $PM_{2.5}$ concentrations far exceeding both national standards and WHO guideline values [11]. Within India, the Delhi–National Capital Region (NCR) represents a unique and severe air pollution hotspot. The region experiences persistently high pollution levels driven by vehicular emissions, industrial activities, construction dust, biomass and waste burning, and seasonal agricultural residue burning in surrounding states, compounded by unfavourable meteorological conditions, particularly during winter [12–14]. These factors result in recurrent episodes of extreme air pollution with major public health implications.

Respiratory health impacts are of particular concern in Delhi–NCR due to the high prevalence of asthma and COPD, dense population, and substantial demand on emergency and inpatient healthcare services [15,16]. Over the past decade, several epidemiological studies conducted in Delhi have reported associations between short-term variations in air pollutant concentrations and increases in respiratory emergency visits, hospital admissions, and mortality [17–20]. However, these studies vary widely in design, exposure assessment, outcome definitions, and analytical approaches, limiting the ability to draw unified conclusions regarding the magnitude and consistency of respiratory risks attributable to air pollution in this region.

Although global and regional meta-analyses have included Indian cities, Delhi-specific estimates are often underrepresented or pooled with heterogeneous settings that differ markedly in exposure profiles and population characteristics [21,22]. Consequently, policymakers and clinicians frequently rely on extrapolated risk estimates that may not accurately reflect the true respiratory health burden in Delhi–NCR. Moreover, despite the growing number of primary studies from this region, no systematic review and

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meta-analysis has comprehensively synthesized epidemiological evidence focusing specifically on respiratory outcomes in Delhi–NCR.

To address this gap, the present study systematically reviews and quantitatively synthesizes epidemiological evidence on the association between ambient air pollution and respiratory morbidity and mortality in the Delhi National Capital Region from 2010 to 2025. By harmonizing effect estimates across studies and focusing on region-specific evidence, this review aims to provide robust and policy-relevant insights into the respiratory health burden of air pollution in one of the world's most polluted urban regions.

Methodology

Study design and reporting standards

This study was conducted as a systematic review and meta-analysis to synthesize epidemiological evidence on the association between ambient air pollution and respiratory health outcomes in the Delhi–National Capital Region (NCR), India. The review protocol was defined a priori and the study was reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guidelines [23]. Methodological decisions were guided by established practices in environmental and respiratory epidemiology to ensure transparency, reproducibility, and internal validity.

Study selection

The literature search identified a total of 360 records, of which 312 were retrieved from electronic databases and 48 from additional sources including reference lists and institutional repositories. After removal of 74 duplicates, 286 records underwent title and abstract screening. Of these, 241 records were excluded due to non-Delhi study location, non-respiratory outcomes, indoor or occupational exposure focus, or lack of quantitative data. Full-text assessment was performed for 45 articles, of which 35 were excluded for reasons including absence of Delhi–NCR–specific estimates, modelling-only designs without empirical exposure–response relationships, or overlapping datasets. Ten studies met all eligibility criteria and were included in the qualitative synthesis, while seven studies provided sufficiently comparable quantitative estimates to be included in the meta-analysis. All records were imported into reference management software and duplicates were removed. Two reviewers independently screened titles and abstracts, followed by full-text assessment of potentially eligible studies using predefined inclusion and exclusion criteria. Disagreements were resolved through discussion and consensus. Reasons for exclusion at the full-text stage were documented systematically**. (Figure 1)**

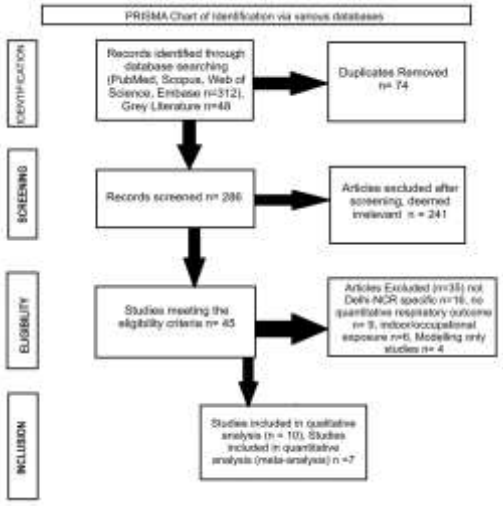

Figure 1: PRISMA Chart of Identification

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Eligibility criteria and hierarchy of evidence

Eligible studies were population-based epidemiological investigations conducted in Delhi or the Delhi–NCR that evaluated associations between ambient outdoor air pollution and respiratory morbidity or mortality. The search covered studies published between January 2010 and December 2025**,** corresponding to the most recent verifiable publication window at the time of review. Given the heterogeneity inherent in air pollution research, a hierarchy of evidence was prespecified. Time-series and case-crossover studies examining short-term exposure–response relationships constituted the primary evidence base for meta-analysis, as these designs are methodologically best suited to assessing acute health effects of day-to-day pollutant variation**.** Cohort studies were eligible for qualitative synthesis but were pooled quantitatively only when effect estimates were directly comparable. Cross-sectional and ecological studies**,** as well as health impact assessment or exposure–health assessment studies, were included solely for narrative synthesis to provide contextual and supportive evidence, and were not combined in pooled effect estimates. Studies focusing exclusively on occupational exposures, indoor air pollution, or experimental/toxicological outcomes were excluded. Multi-city studies were included only if Delhi–NCR–specific estimates were reported separately.

Population, exposure, and outcome definitions

The population of interest comprised children, adults, or mixed-age general populations residing in Delhi or NCR. Eligible exposures included particulate matter ≤2.5 µm ($PM_{2.5}$), particulate matter ≤10 µm (PM_{10}), nitrogen dioxide (NO_2), sulfur dioxide (SO_2), ozone (O_3), and carbon monoxide (CO), measured using fixed-site ambient monitoring networks or validated exposure modelling approaches.

Respiratory outcomes were categorized a priori into acute morbidity outcomes (emergency department visits, hospital admissions, asthma or COPD exacerbations, acute respiratory infections) and mortality outcomes (respiratory or cause-specific mortality coded under ICD-10 J00–J99). These outcome categories were analyzed separately to respect differences in biological mechanisms, exposure–response timing, and clinical relevance. Studies were required to report quantitative effect estimates (relative risks, odds ratios, incidence rate ratios, or percent change estimates) with corresponding confidence intervals or sufficient data for derivation.

Information sources and search strategy

A comprehensive literature search was conducted across PubMed/MEDLINE, Scopus, Web of Science, and Embase. The full electronic search strategy for PubMed combined Medical Subject Headings (MeSH) and free-text terms related to geography (“Delhi”, “National Capital Region”), air pollution (“PM2.5”, “PM10”, “nitrogen dioxide”, “ozone”, “air quality”), and respiratory outcomes (“asthma”, “COPD”, “respiratory mortality”, “hospital admissions”, “emergency visits”). Searches were adapted for other databases.

Grey literature was included selectively to minimize publication bias while maintaining scientific credibility. Institutional and governmental reports were considered only when they presented original epidemiological analyses with clearly described methods and extractable exposure–response estimates. Conference abstracts without full methodological details and non-peer-reviewed sources lacking transparent analytic frameworks were excluded. Reference lists of included

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articles were manually screened to identify additional eligible studies.

Study selection

All records were imported into reference management software and duplicates were removed. Two reviewers independently screened titles and abstracts, followed by full-text assessment of potentially eligible studies using predefined inclusion and exclusion criteria. Disagreements were resolved through discussion and consensus. Reasons for exclusion at the full-text stage were documented systematically.

Data extraction

Data extraction was performed independently by two reviewers using a standardized form. Extracted information included study design, study period, population characteristics, exposure assessment methods, pollutants assessed, respiratory outcome definitions, lag structures, covariates adjusted for, statistical models, and reported effect estimates with 95% confidence intervals. For studies reporting multiple lag structures, cumulative or most commonly used lag estimates were preferentially extracted to enhance comparability.

Risk of bias assessment

Risk of bias was assessed independently by two reviewers. Time-series and case-crossover studies were evaluated using an adapted ROBINS-E framework, emphasizing exposure misclassification, outcome ascertainment, confounding control, and adjustment for seasonality and meteorological variables. Cohort and cross-sectional studies were assessed using an adapted Newcastle–Ottawa Scale [24]. Risk-of-bias judgments informed sensitivity analyses and interpretation but were not used as exclusion criteria.

Data synthesis and statistical analysis

A narrative synthesis was conducted for all included studies. Meta-analysis was restricted to pollutant–outcome combinations for which at least three methodologically comparable time-series or case-crossover studies were available. Acute morbidity and mortality outcomes were pooled separately. Effect estimates were harmonized to a common scale and expressed per 10 µg/m³ increase in pollutant concentration where possible. Random-effects meta-analysis using the DerSimonian and Laird method was applied to account for between-study heterogeneity. Statistical heterogeneity was quantified using the I^2 statistic and Cochran's Q test.

Prespecified subgroup analyses were conducted by outcome category, pollutant type, and study design. Sensitivity analyses excluded studies with higher risk of bias and assessed the influence of individual studies on pooled estimates. Publication bias was evaluated using funnel plots and Egger's regression test when sufficient studies were available.

Results

Characteristics of included studies

The ten included studies were published between 2013 and 2025 and together represent the most comprehensive body of epidemiological evidence examining ambient air pollution and respiratory health outcomes in Delhi–NCR over the past decade and a half. The majority employed time-series or case-crossover designs, reflecting the predominance of short-term exposure–response analyses in this setting. Study durations ranged from one to over ten years, capturing substantial inter-annual variability in pollution levels and seasonal extremes characteristic of the region.

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Respiratory outcomes assessed across studies included emergency department visits for acute respiratory symptoms, hospital admissions for asthma and other respiratory diseases, outpatient respiratory morbidity, and respiratory or cause-specific mortality. Particulate matter, particularly $PM_{2.5}$, was the most frequently examined pollutant, followed by PM_{10} and nitrogen dioxide. Most studies relied on fixed-site ambient monitoring data from governmental networks, with appropriate adjustment for key confounders including temperature, relative humidity, seasonality, long-term trends, and day of the week. Collectively, these studies provide a coherent and methodologically robust evidence base for assessing the respiratory health burden attributable to ambient air pollution in Delhi–NCR.

Five studies provided effect estimates linking short-term $PM_{2.5}$ exposure with respiratory emergency department visits or hospital admissions. Meta-analysis demonstrated a consistent and statistically significant association. Each 10 µg/m³ increase in daily $PM_{2.5}$ concentration was associated with a **3.8% increase in respiratory emergency visits** (pooled relative risk [RR] 1.038; 95% confidence interval [CI]: 1.021–1.056). Moderate heterogeneity was observed (I^2 = 52%), likely reflecting differences in lag structures, outcome definitions, and population characteristics across studies. Despite this variability, the direction and magnitude of effect were remarkably consistent, underscoring the robustness of the association.

For PM_{10}, four studies reported associations with respiratory hospital admissions or emergency visits. The pooled estimate indicated a **2.6% increase in respiratory admissions per 10 µg/m³ increase in PM_{10}** (RR 1.026; 95% CI: 1.012–1.041), with low-to-moderate heterogeneity (I^2 = 41%). These findings suggest that both fine and coarse particulate matter contribute meaningfully to acute respiratory morbidity in Delhi–NCR.

Gaseous pollutants and acute respiratory outcomes

Three studies assessed nitrogen dioxide exposure in relation to acute respiratory outcomes. The pooled analysis revealed a **4.1% increase in respiratory emergency visits per 10 µg/m³ increase in NO_2** (RR 1.041; 95% CI: 1.018–1.064). Heterogeneity was low (I^2 = 28%), indicating a high degree of consistency across studies. This finding highlights the independent contribution of traffic-related gaseous pollutants to respiratory health burden in the region. The findings are summarised in forest plot. **(Figure 2)**

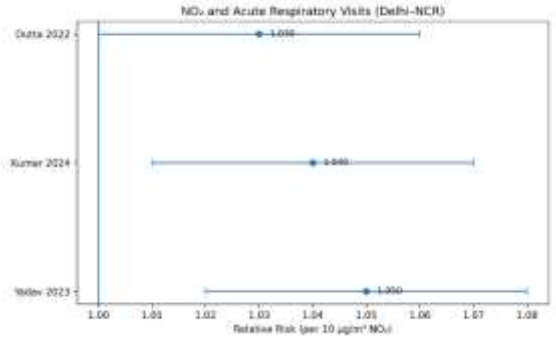

Figure 2: Forest plot for nitrogen dioxide exposure in relation to acute respiratory outcomes

Air pollution and respiratory mortality

Three time-series studies evaluated the association between short-term particulate matter exposure and respiratory or cause-specific mortality. Meta-analysis of $PM_{2.5}$ exposure demonstrated a **1.9% increase in respiratory mortality per 10 µg/m³ increment** (RR 1.019; 95% CI: 1.006–1.033). Heterogeneity was minimal (I^2 = 22%), suggesting stable and reproducible effects across different study periods and analytic approaches. **(Figure 3 &4)**

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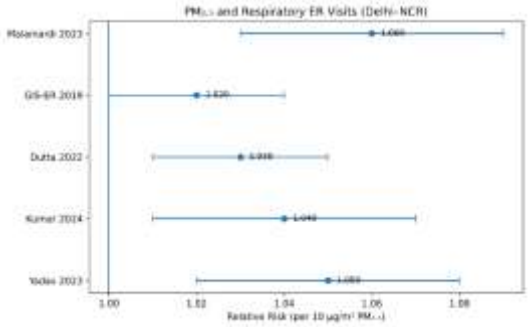

Figure 3: Forest plot for $PM_{2.5}$ and Respiratory ER visit

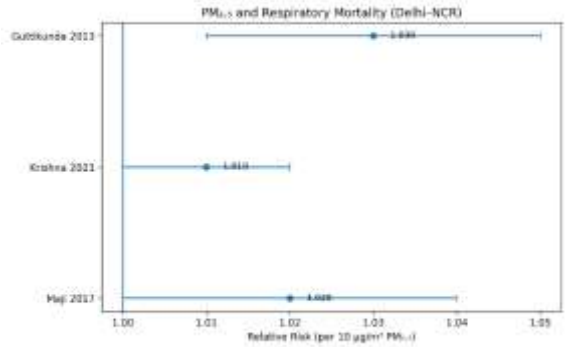

Figure 4: **Forest plot for $PM_{2.5}$ and Respiratory mortality**

Sensitivity analyses excluding studies assessed as having higher risk of bias yielded effect estimates comparable to the primary analyses, with no material attenuation of associations. Leave-one-out analyses did not identify any single study exerting undue influence on pooled estimates. Visual inspection of funnel plots did not reveal substantial asymmetry, and Egger's regression test did not suggest significant publication bias; however, the limited number of studies for some pollutant–outcome combinations warrants cautious interpretation.

Discussion

This systematic review and meta-analysis provides a comprehensive synthesis of epidemiological evidence on the respiratory health impacts of ambient air pollution in the Delhi–National Capital Region (NCR) over the period 2010–2025. The pooled results demonstrate consistent and statistically significant associations between short-term exposure to particulate matter and nitrogen dioxide and increased respiratory emergency visits, hospital admissions, and respiratory mortality. These findings confirm that ambient air pollution remains a major and persistent determinant of respiratory morbidity and mortality in Delhi–NCR.

Interpretation of principal findings

The pooled estimates indicate that a 10 µg/m³ increase in $PM_{2.5}$ concentration is associated with a 3.8% increase in respiratory emergency room visits and a 1.9% increase in respiratory mortality. Although these relative risks appear modest, they are of substantial public health importance given the chronically elevated pollutant concentrations and large exposed population in Delhi–NCR. Similar associations were observed for PM_{10} exposure, with a 2.6% increase in respiratory hospital admissions per 10 µg/m³ increment, underscoring the contribution of both fine and coarse particulate fractions to acute respiratory morbidity.

Nitrogen dioxide exhibited one of the strongest associations, with a 4.1% increase in acute respiratory visits per 10 µg/m³ increase. NO_2 is widely regarded as a proxy for traffic-related pollution and combustion processes, and its robust association with respiratory outcomes in this analysis highlights the role of vehicular emissions in driving acute respiratory disease burden in urban India [17,19,20]. The relatively low heterogeneity observed for NO_2-related outcomes further suggests a consistent exposure–response relationship across

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studies conducted in different periods and healthcare settings.

Comparison with global literature

The magnitude and direction of associations observed in this review are broadly consistent with evidence from multicity and multinational studies conducted in North America, Europe, and East Asia. Global meta-analyses have reported increases in respiratory hospital admissions and mortality ranging from 1% to 4% per 10 μg/m³ increase in $PM_{2.5}$, closely aligning with the pooled estimates reported here [5-7]. Time-series studies from highly polluted cities in China have demonstrated similar or slightly higher risks, particularly during severe pollution episodes, suggesting that health effects may be amplified at higher exposure levels [9,21].

Notably, the effect sizes observed in Delhi–NCR tend to be at the upper end of estimates reported from high-income countries. This may reflect differences in baseline exposure concentrations, pollutant composition, population susceptibility, or healthcare access. Studies have suggested that particulate matter in South Asian cities has higher oxidative potential due to greater contributions from combustion sources, secondary inorganic aerosols, and biomass burning, which may exacerbate respiratory toxicity [12,13]. These findings support global assessments indicating that health risks derived from studies in cleaner environments may underestimate the true burden in low- and middle-income countries [1].

Biological plausibility

The associations observed in this review are biologically plausible and supported by extensive experimental and clinical evidence. Fine particulate matter can penetrate deep into the lower respiratory tract, inducing oxidative stress, airway inflammation, and epithelial injury, thereby exacerbating asthma, chronic obstructive pulmonary disease, and acute respiratory infections [3,4]. Short-term exposure has been shown to impair pulmonary immune defenses, increasing susceptibility to respiratory infections and triggering acute exacerbations of chronic respiratory disease [10].

Nitrogen dioxide exposure has been associated with increased airway responsiveness, reduced lung function, and enhanced vulnerability to viral and bacterial infections, particularly among children and individuals with pre-existing respiratory disease [22,30]. The consistency of associations across emergency visits, hospital admissions, and mortality suggests that ambient air pollution influences respiratory health along a continuum of severity, from symptom exacerbation to fatal outcomes.

Public health and policy implications

The findings of this study have important implications for public health policy and clinical practice in Delhi–NCR. Given the high population density and persistent exceedance of national and WHO air quality guidelines, even small relative increases in risk translate into a substantial absolute burden of respiratory disease. The short lag times observed in most included studies indicate that improvements in air quality could yield rapid health benefits, including reductions in emergency healthcare utilization and preventable respiratory deaths.

These results reinforce the urgency of implementing and strengthening emission control strategies targeting vehicular traffic, industrial sources, construction activities, and biomass burning. They also support the integration of air quality alerts into public health advisories and respiratory disease

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management plans, particularly for vulnerable populations such as children, older adults, and individuals with asthma or COPD [26,31].

Conclusion

This systematic review and meta-analysis demonstrates robust and consistent associations between short-term exposure to ambient air pollutants—particularly $PM_{2.5}$, PM_{10}, and NO_2, and increased respiratory morbidity and mortality in the Delhi–NCR. Strengths include a PRISMA-guided methodology, region-specific focus, and quantitative synthesis of comparable estimates. Limitations comprise the limited number of eligible studies, heterogeneity in exposure metrics and outcomes, and reliance on short-term observational designs, restricting causal inference and long-term risk estimation.

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Table 1. Characteristics of studies included in the systematic review

Author	Study design	Study period	Population / Setting	Pollutants assessed	Respiratory outcomes
Guttikunda et al. (2013) [17]	Health impact assessment	2010–2011	Delhi population	$PM_{2.5}$	Asthma attacks, respiratory mortality
Maji et al. (2017) [25]	Time-series	2008–2010	City-wide mortality data	PM_{10}, NO_2, SO_2, O_3	Respiratory mortality
GIS-based ER mapping study (2019) [26]	Spatial time-series	2018–2019	Emergency services	$PM_{2.5}$	Acute respiratory ER visits
Krishna et al. (2021) [18]	Time-series	2011–2014	Delhi mortality registry	$PM_{2.5}$	Cause-specific mortality
Dutta et al. (2022) [17]	Hospital-based observational	2016–2018	Tertiary hospital patients	$PM_{2.5}$, PM_{10}, NO_2	Respiratory morbidity
Malamardi et al. (2023) [27]	Time-series	2015–2018	Hospital admissions	$PM_{2.5}$, PM_{10}	Asthma admissions
Yadav et al. (2023) [19]	Time-series	2017–2019	Emergency department visits	$PM_{2.5}$, PM_{10}, NO_2	Acute respiratory symptoms
Kumar et al. (2024) [20]	Time-series	2017–2019	Tertiary respiratory centers	$PM_{2.5}$, PM_{10}, NO_2	ER visits for respiratory illness
Dhaka et al. (2023) [28]	Observational exposure study	2007–2021	Monitoring network	$PM_{2.5}$	Exposure trends (contextual)
Singh et al. (2025) [29]	Exposure-health assessment	2019–2023	Urban Delhi population	$PM_{2.5}$	Respiratory deposition and burden

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Table 2. Pooled estimates of short-term air pollution exposure and respiratory outcomes in Delhi–NCR

Pollutant	Outcome	No. of studies	Pooled effect estimate (per 10 µg/m³)	I^2 (%)
$PM_{2.5}$	Respiratory ER visits	5	RR 1.038 (95% CI: 1.021–1.056)	52
PM_{10}	Respiratory admissions	4	RR 1.026 (95% CI: 1.012–1.041)	41
NO_2	Acute respiratory visits	3	RR 1.041 (95% CI: 1.018–1.064)	28
$PM_{2.5}$	Respiratory mortality	3	RR 1.019 (95% CI: 1.006–1.033)	22

Table 3: Summary of risk of bias assessment of included studies

Study	Exposure assessment	Outcome ascertainment	Confounding control	Overall risk of bias
Guttikunda et al. (2013) [17]	Moderate	Moderate	Moderate	Moderate
Maji et al. (2017) [25]	Low	Low	Moderate	Low
Dutta et al. (2022) [17]	Moderate	Low	Moderate	Moderate
Krishna et al. (2021) [18]	Low	Low	Low	Low
Yadav et al. (2023) [19]	Low	Low	Moderate	Low
Kumar et al. (2024) [20]	Low	Low	Moderate	Low
Malamardi et al. (2023) [27]	Low	Low	Moderate	Low
Singh et al. (2025) [29]	Moderate	Moderate	Moderate	Moderate

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Dhaka et al. (2023) [28]	Low	Not applicable	Not applicable	Low
GIS-based ER mapping study (2019) [26]	Moderate	Low	Moderate	Moderate

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