International Journal of
Pollution: Prevention & Control

ISSN: 3048-6750
Volume 4, Issue 1, 2026
January–June
DOI (Journal):10.37591/IJPPC

https://journals.stmjournals.com/ijppc

Review IJPPC

Unveiling Bihar's Atmospheric Crisis: A Synoptic Review of PM2.5 Dynamics, Source Attribution, and Airshed Vulnerabilities in the Eastern Indo-Gangetic Plain (Bihar)

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Abstract

Bihar, situated in the pollution-trapping Indo-Gangetic Plain (IGP), faces a severe air pollution crisis characterized by annual PM2.5 concentrations of 80–100 µg m^{-3} exceeding WHO guidelines (5 µg m^{3}) and Indian National Ambient Air Quality Standard (NAAQS) (40 µg m^{-3}) by 4–6-fold. This review synthesizes data from CPCB/BSPCB monitoring, MODIS satellite retrievals, and peer-reviewed studies (2000–2025) to assess ambient air quality, sources, health impacts, policies, and research gaps in the state. PM2.5 and PM10 dominate, with rural levels rivaling urban centers like Patna (80–90% poor air quality index (AQI) days in winter/post-monsoon). Source apportionment reveals brick kilns (6,500+ units, 15–35% PM2.5), biomass burning (70% rural households), vehicular emissions, and transboundary inflows from UP/WB as key drivers. Winter inversions and declining rainfall exacerbate stagnation. Health burdens include respiratory/cardiovascular diseases, anemia (10–15% higher near kilns), and ~2% gross state domestic product (GSDP) loss from premature mortality/productivity declines. Vulnerable groups-children, the elderly, and rickshaw pullers-face disproportionate risks. National Clean Air Program (NCAP) action plans promote zigzag kilns (82–85% adoption, 50–75% PM cuts), compressed natural gas (CNG)/EVs, and Continuous Ambient Air Quality Monitoring Stations (CAAQMS) expansion, yet implementation lags. Challenges persist in rural monitoring gaps, speciation deficits, and feedback on climate pollution. This review calls for airshed-level management across IGP states, integrating dense sensors, emission inventories, and coupled climate-air models to achieve sustainable air quality improvements and co-benefits for health/economy.

Keywords: Air pollution, Bihar, Brick kiln emissions, Indo-Gangetic Plain, PM2.5

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Received Date: January 13, 2026
Accepted Date: January 16, 2026
Published Date: February 07, 2026

Citation: Krishna Roy, Amrita Raj Bharti, Umakant Kumar, Animesh Kumar, Shashi Prabha Dubey. Unveiling Bihar's Atmospheric Crisis: A Synoptic Review of PM2.5 Dynamics, Source Attribution, and Airshed Vulnerabilities in the Eastern Indo-Gangetic Plain (Bihar). International Journal of Pollution: Prevention & Control. 2026; 4(1): 1–10p.

INTRODUCTION

Ambient air pollution is now recognized as the leading global environmental risk factor, responsible for an estimated 6–7 million premature deaths annually [1], largely due to exposure to fine particulate matter and ozone. At the national scale, India contributes substantially to this global burden [2], with Punjab (19%), Haryana (13%), and Indo-Gangetic Plain (IGP) states such as Uttar Pradesh (39%), Bihar (17%), West Bengal (13%), and Delhi (0.9%) [3], recording some of the highest annual mean PM2.5, frequently exceeding both the WHO Air Quality Guidelines and the Indian National Ambient Air Quality Standards (NAAQS) [4]. The launch of India's National Clean Air Program

(NCAP) in 2019, with a targeted 20–30% reduction in PM2.5/PM10 concentrations relative to 2017 levels in 131 non-attainment cities by 2024 and now extended to 2026–2030, reflects the policy recognition of this escalating crisis [5].

Bihar occupies a strategic yet vulnerable position in the eastern IGP, characterized by low relief, fertile alluvial soils, and a dense river network dominated by the Ganga and its tributaries, which together create a basin-like topography that favors stagnation and pollutant accumulation during stable winter conditions. Rapid population growth (over 124 million people, with a high density exceeding 1,100 persons per sq km), combined with low urbanization (~11–12%), produces a hybrid emission profile where urban transport and construction coexist with pervasive rural biomass use, small-scale industry, and brick manufacturing. Emerging sensor network studies demonstrate that rural Bihar now experiences PM2.5, which is comparable to or even worse than that in its cities, contradicting the historic urban-centric bias in monitoring networks [6].

Bihar's inclusion of multiple non-attainment cities under NCAP, notably Patna, Gaya, Muzaffarpur, and more recently, Munger and Hajipur, underscored its importance as a regional air pollution hotspot with complex local and transboundary source contributions [7]. The combination of high baseline vulnerability (poverty, undernutrition, limited health care access) and elevated exposure implies that the attributable health and economic burdens of air pollution are disproportionately high in the state, with economic losses estimated at 2% of the state's gross domestic product (GDP) in 2019 alone. This review focuses on Bihar to synthesize the current understanding of ambient air quality patterns, source apportionment, health, socioeconomic impacts, and policy responses, while highlighting key data gaps and priority areas for future research and airshed-level management.

CURRENT STATE OF AMBIENT AIR QUALITY

Available measurements consistently show that PM2.5 and PM10 are the dominant criteria pollutants driving poor air quality in Bihar [8], while gaseous pollutants such as NO_2 and SO_2 generally remain below the NAAQS limits but still contribute to secondary aerosol formation and health risks in Figure 1 [9]. Long-term analyses of satellite-derived PM2.5, for 2010–2025, indicate a monotonic increase in particulate concentrations over most districts, with recent annual means often exceeding 80–100 $\mu g\ m^{-3}$ [10], roughly 4–6 times the WHO 2021 guideline value of 5 $\mu g\ m^{-3}$ [11], and 2–3 times the Indian annual standard of 40 $\mu g\ m^{-3}$ for PM2.5 [12, 13].

Spatially, higher PM2.5 burdens are observed in northern and central Bihar, where dense clusters of traditional brick kilns, sugar mills, and agricultural burning intersect with rapidly urbanizing towns such as Patna, Darbhanga, etc. [14, 15], whereas southern districts show comparatively lower but still unhealthy levels influenced by industrial activities and biomass use [16]. Within urban areas, cities such as Patna and Hajipur experience sharper diurnal peaks driven by traffic, commercial activities, and resuspended dust from construction [17], whereas peri-urban and rural sites show sustained evening and early morning peaks linked to domestic biomass burning for cooking and space heating [18]. Seasonal analyses revealed pronounced winter smog episodes associated with shallow mixing layers, low wind speeds, and temperature inversions that trap pollutants near the surface, as well as post-monsoon spikes attributable to open burning of rice and wheat residues within Bihar and in the upwind regions of northwest India [19, 20].

When benchmarked against international standards, Bihar's annual PM2.5 levels are among the highest globally, often comparable to or exceeding those reported for the most polluted city clusters in China before the implementation of aggressive control measures, underscoring the urgency of enhanced regional management [21]. Even short-term 24-h average PM2.5 and PM10 concentrations during winter inversion episodes surpass WHO interim targets and Indian NAAQS by factors of 3–5, implying substantial acute health risks, particularly for vulnerable groups with pre-existing cardiopulmonary conditions [22]. The combination of high baseline concentrations, strong seasonality, and rapidly growing urban infrastructure suggests that without significant emission reductions in Table 1, Bihar is unlikely to meet NCAP-linked reduction targets in the near term, as shown in Figure 2 [23–28].

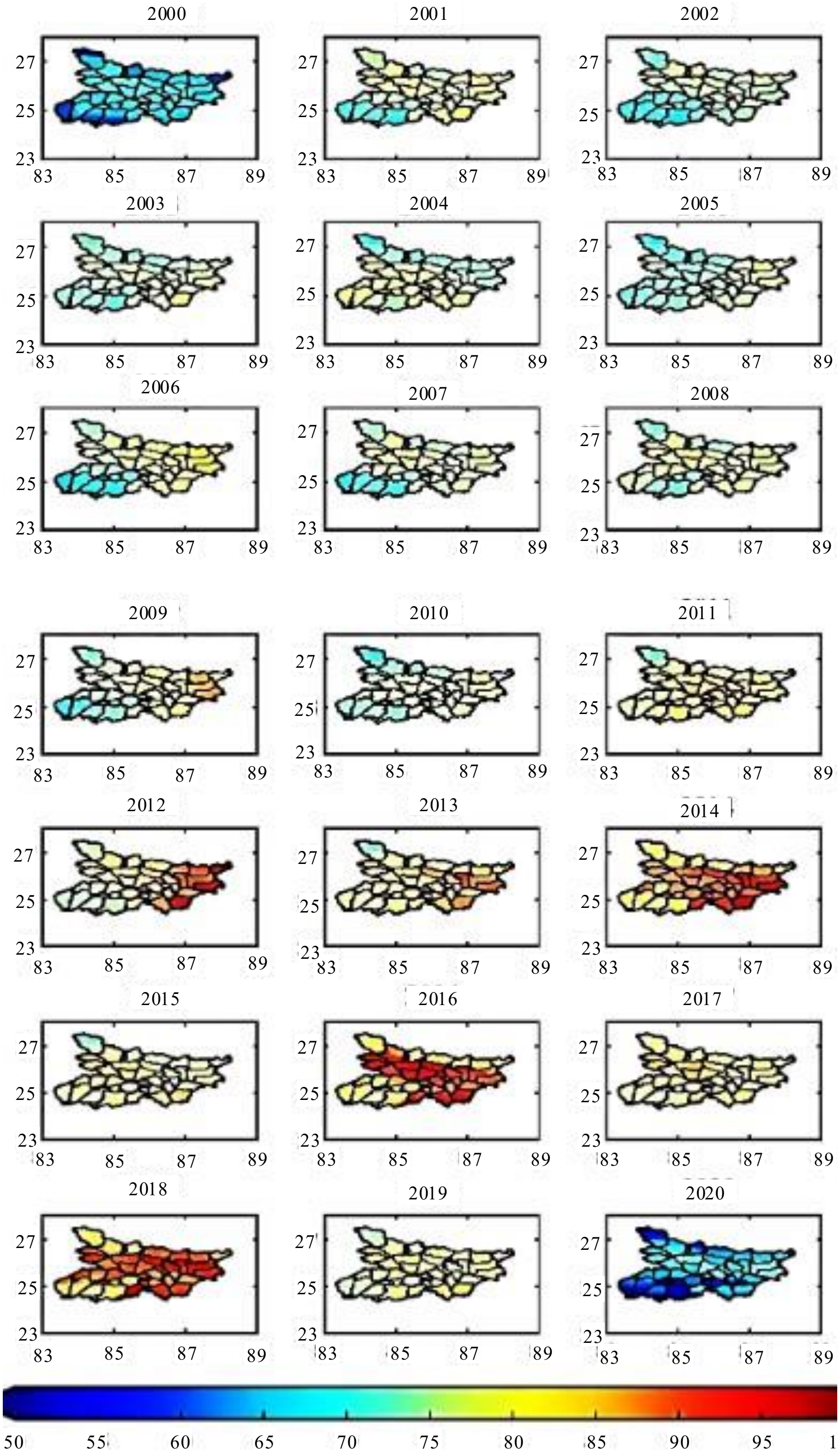

Figure 1. Annual trends and fluctuations over twenty years (2000–2020) of PM2.5 concentrations in Bihar [13].

Table 1. Comparative annual average PM2.5 concentrations (μg m^{-3}) annual National Ambient Air Quality Standard (NAAQS) = 40 μg m^{-3}, WHO guideline = 5 μg m^{-3}.

City	2023 (avg.)	2024 (avg.)	2025 (avg.)	% Change (2023–2025)	Status
Patna	125.1	73.7	71.2	-43%	Non-attainment
Muzaffarpur	138.4	88.2	84.5	-39%	Non-attainment
Begusarai	148.3	55.1	51.8	-65%	Significant Improvement
Gaya	94.2	68.5	65.0	-31%	Non-attainment
Bhagalpur	110.5	76.4	72.3	-34%	Industrial Hub
Arrah	84.5	49.2	46.8	-44%	Approaching NAAQS
Katihar	89.6	49.5	47.2	-47%	Improved
Bettiah	86.2	48.0	45.5	-47%	Improved
Siwan	102.3	82.5	79.8	-22%	Critical (Winter)
Hajipur	118.0	74.2	70.5	-40%	Non-attainment

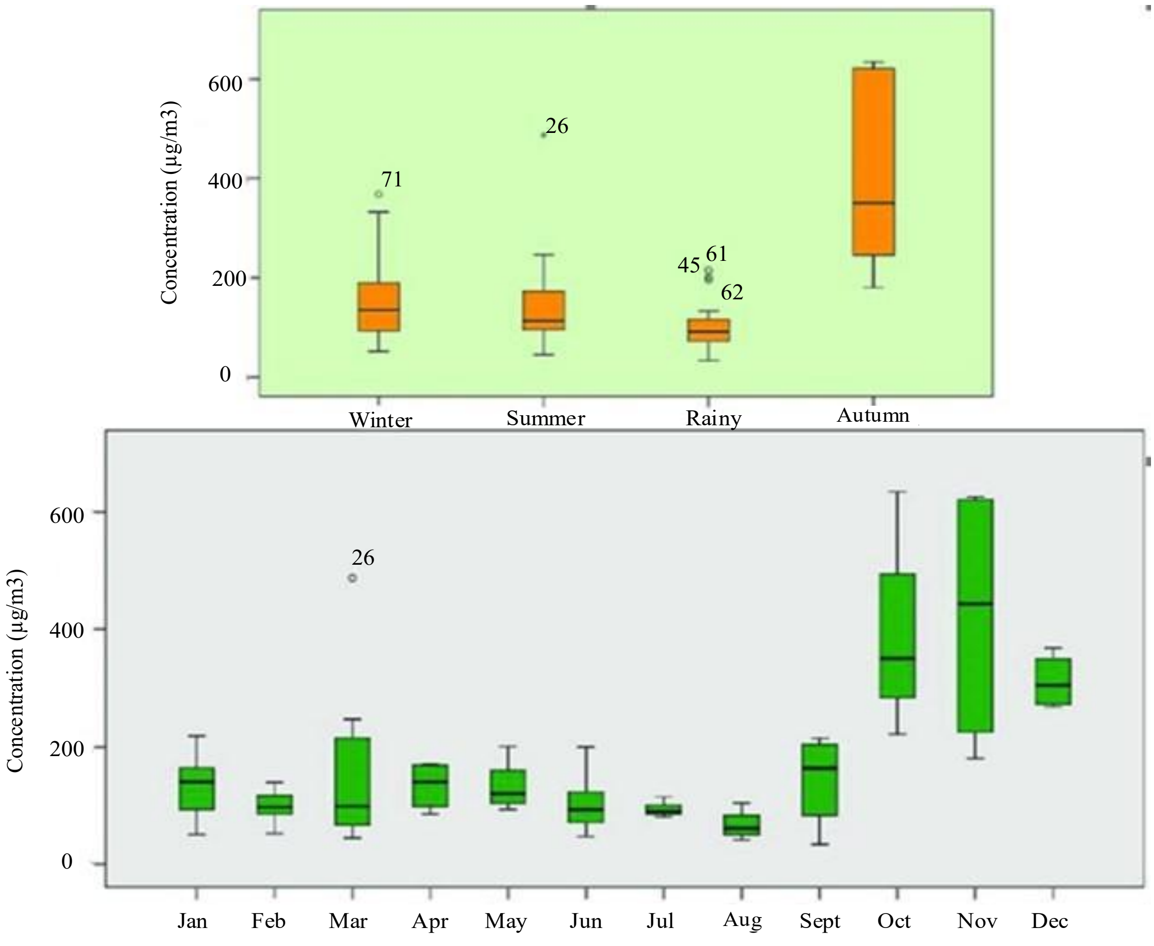

Figure 2. Seasonal PM2.5 variations in Patna: A box-plot analysis showing peak pollution levels in winter and the lowest concentrations during the monsoon.

Source Apportionment (Major Drivers)

Natural sources in Bihar are dominated by mineral dust originating from the extensive alluvial deposits of the Ganga Basin, riverbed sediments, and exposed agricultural fields, especially during the pre-monsoon and summer periods, when strong winds and low vegetation cover facilitate resuspension. This crustal component contributes substantially to coarse PM2.5/PM10 and a larger fraction of PM2.5–10, with elemental analyses from IGP-wide receptor studies indicating enriched levels of calcium, silicon, and aluminum, consistent with soil dust signatures [28]. However, recent work suggests that secondary inorganic aerosols (sulfate, nitrate, ammonium) and primary carbonaceous particles now dominate the fine PM2.5 fraction across much of the IGP, including Bihar, highlighting the increasing importance of anthropogenic combustion sources over purely natural dust contributions [29].

Among anthropogenic sources, the transport sector contributes significantly to urban centers such as Patna, Gaya, Muzaffarpur, and Gopalganj, where mixed fleets of two-wheelers, aging diesel buses, freight trucks, and auto rickshaws operate with limited inspection and maintenance, leading to elevated primary PM2.5/PM10, black carbon, and NOx emissions [30]. Occupational groups exposed to traffic, such as traffic police and rickshaw pullers, show higher respiratory symptoms and impaired lung function, consistent with chronic exposure to roadside concentrations that far exceed ambient background levels [31]. Small-scale industries and power plants contribute regionally, but brick kilns represent a particularly important stationary source, with thousands of largely traditional Bull's Trench and clamp kilns operating seasonally around Bihar's cities and along river corridors [16, 18]. The transition to induced draft zigzag kiln technology under regulatory pressure has begun to reduce specific emissions, yet many units still operate with suboptimal firing and poor enforcement, sustaining a large PM and black carbon footprint.

The household use of solid biomass fuels (wood, dung cakes, crop residues) and coal for cooking and heating remains pervasive in rural Bihar, with clean-fuel penetration constrained by affordability and supply reliability, thereby generating substantial primary particulate and gaseous emissions that contribute to both indoor and neighborhood-scale outdoor pollution. Seasonal burning of agricultural residues in paddy-wheat systems, particularly in southwest and southeast Bihar, combined with the transboundary inflow of smoke from Punjab, Haryana, and Uttar Pradesh, further amplifies post-monsoon PM2.5 [32, 33]. Dust from construction and road work, often conducted without adequate wet suppression or covering, adds a persistent coarse particle burden in rapidly expanding urban and peri-urban corridors [34], while informal waste burning introduces toxic organic and heavy metal-laden aerosols into local airsheds. Overall, source apportionment studies in the broader IGP attribute roughly half or more of urban PM2.5 to anthropogenic combustion sources (transport, industry, brick kilns, biomass), implying substantial potential for emission reductions through targeted technology and behavioral interventions.

Health and Socioeconomic Impacts

The disease burden attributable to air pollution in India is substantial, with integrated exposure-response modeling linking elevated PM2.5 and ozone concentrations to increased mortality and morbidity from ischemic heart disease, stroke, chronic obstructive pulmonary disease (COPD), lower respiratory infections, and lung cancer [35–38]. Bihar is among the states with the highest economic loss from air pollution-related disease burden relative to its gross state domestic product (GSDP); estimates for 2019 suggest that the lost output from premature deaths and morbidity attributable to ambient and household air pollution together amounted to nearly 2% of Bihar's GSDP, surpassing the national average of 1.36% of GDP. This disproportionate loss reflects the combination of high exposure, young population structure, heavy reliance on manual labor, and limited adaptive capacity, meaning that air pollution undermines both public health and socioeconomic development trajectories in the state, as shown in Figure 3.

Local epidemiological studies, though fewer than those in metropolitan centers, indicate significant associations between particulate exposure and respiratory outcomes in traffic-exposed occupational groups in Bihar, including lung function impairment and an increased prevalence of chronic cough, wheezing, and other respiratory symptoms among traffic police and roadside workers. Children living in highly polluted wards in cities such as Patna and Muzaffarpur face greater risks of acute lower respiratory infections and may experience impaired lung growth, cognitive deficits, and adverse birth outcomes, which is consistent with findings from other IGP cohorts. Elderly populations and individuals with pre-existing cardiovascular or pulmonary disease exhibit heightened susceptibility to pollution peaks during winter smog episodes when hospital visits, emergency admissions, and all-cause mortality tend to rise, although detailed state-level time-series data remain limited.

The economic burden of air pollution in Bihar extends beyond direct healthcare expenditures to include lost workdays, diminished labor productivity, and long-term impacts on human capital formation, such as stunting and reduced educational attainment linked to early life exposure. Businesses across India are estimated to be lost in the order of US$95 billion annually due to pollution-related absenteeism and productivity declines, with low-income, high-pollution states such as Bihar bearing a disproportionate share relative to their economic size. For outdoor workers such as rickshaw pullers, construction workers, and informal sector vendors, prolonged exposure to high PM2.5, combined with a lack of social protection and health insurance, compounds vulnerability and creates a feedback loop in which environmental degradation reinforces poverty and health inequities. Addressing air pollution in Bihar, therefore, offers major benefits in terms of reducing disease burden, enhancing productivity, and promoting more equitable development outcomes.

Policy Framework and Interventions

India's NCAP provides an overarching national framework for air quality management, under which several of Bihar's cities have been notified of non-attainment and mandated to prepare city-specific

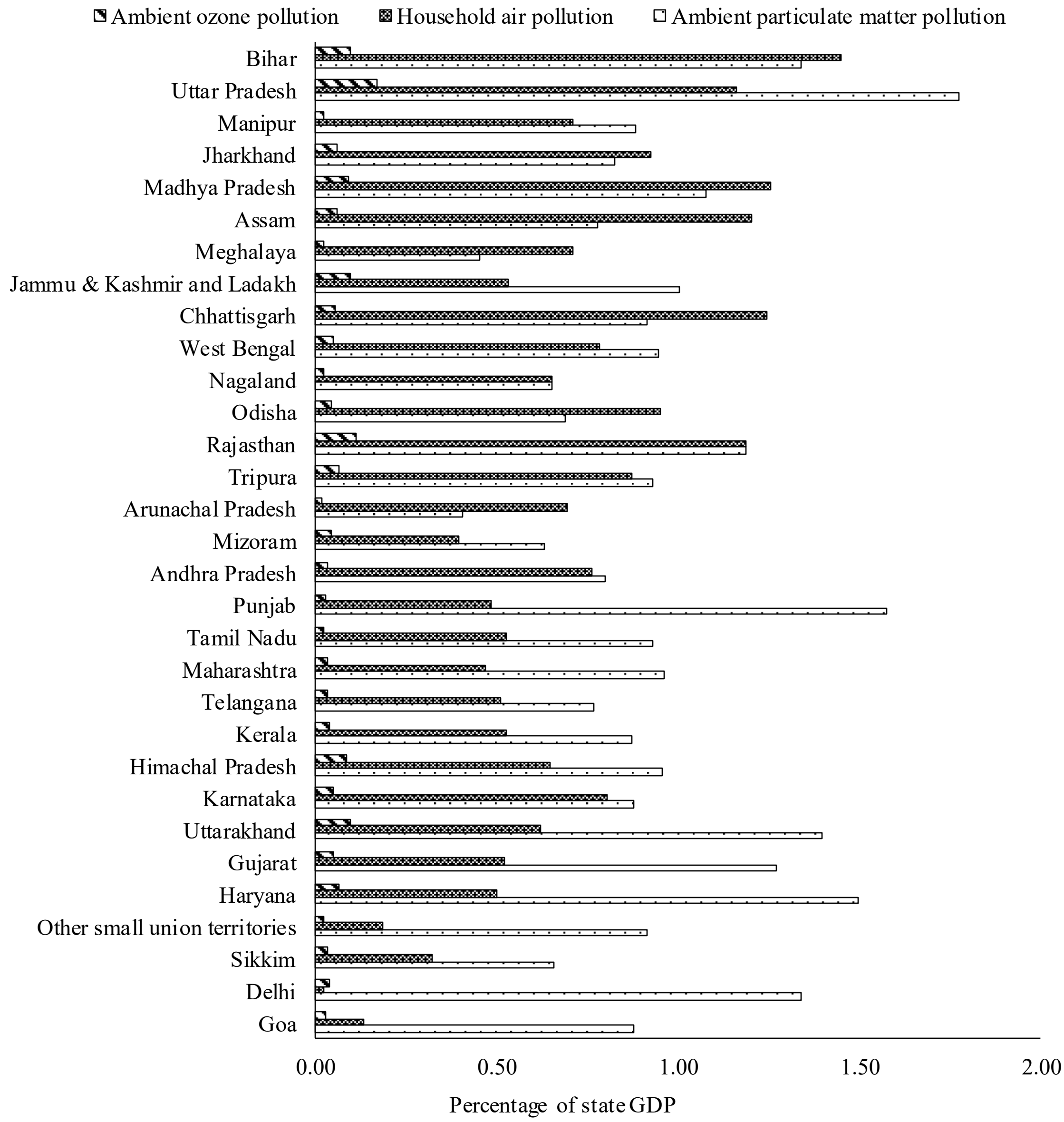

Figure 3. Economic loss as a percentage of State GDP in 2019 resulting from mortality and morbidity caused by ambient particulate matter, household air pollution, and ozone in India [39].

Clean Air Action Plans (CAAPs) with quantified sectoral measures and timelines. Patna, Gaya, and Muzaffarpur have developed CAAPs that include interventions such as strengthening public transport, phasing out old commercial vehicles, greening programs, improved road dust management, and tighter enforcement on brick kilns and industrial units, although their implementation has been uneven and constrained by resource and capacity limitations. At the state level, the Bihar State Pollution Control Board coordinates regulatory measures, including consent-to-operate conditions, stack emission norms, promotion of zigzag technology in brick kilns, and expansion of ambient monitoring networks, while local urban bodies are tasked with municipal-scale actions, such as solid waste management and traffic regulation.

Technological shifts form a key component of mitigation strategies in the transport and industrial sectors of Bihar. The gradual rollout of Bharat Stage VI emission standards for new vehicles, combined with scrappage policies and promotion of compressed natural gas (CNG) and, more recently, electric vehicles (EVs), aims to reduce primary PM2.5 and NOx emissions from the on-road fleet, although the pace of adoption remains slower than in metropolitan regions because of infrastructure and affordability constraints. In the brick kiln sector, regulatory mandates requiring conversion from fixed chimney Bull's Trench kilns to zigzag designs have the potential to reduce PM and black carbon emissions by 30–60% per unit of output, but enforcement challenges and the persistence of informal and seasonal kilns limit the realized benefits. Parallel efforts to expand access to clean household energy through programs such as the Pradhan Mantri Ujjwala Yojana (PMUY) help mitigate household and neighborhood-scale biomass emissions, although sustained adoption in low-income rural households remains a challenge.

Bihar's monitoring infrastructure has expanded from a handful of manual stations to a growing network of CAAQMS in key cities; however, coverage remains sparse relative to the spatial heterogeneity of emissions and exposure across 38 districts. Recent collaborations involving low-cost sensor deployments, such as the AMRIT project, demonstrate the potential of integrating dense sensor data with satellite products and chemical transport models to create high-resolution exposure surfaces that can provide more nuanced, airshed-based management rather than citywide, siloed interventions. Governance discussions at the national level increasingly emphasize the need for airshed-level coordination across administrative boundaries, recognizing that emissions in upwind states and neighboring countries substantially influence Bihar's air quality, and that effective control requires coordinated planning, joint monitoring, and shared accountability mechanisms.

Challenges and Future Research Directions

Despite recent advances, significant data gaps have hindered the comprehensive assessment and management of air pollution in Bihar. Long-term, chemically speciated aerosol measurements are scarce, limiting their ability to differentiate between primary and secondary particles, fossil fuels, and biomass carbon, and to quantify contributions from key precursors, such as ammonia from agriculture and livestock. Rural monitoring remains particularly inadequate in the official network, even though new sensor studies show that rural and small-town populations often experience exposure levels comparable to or greater than those of urban residents, underscoring the need for systematic integration of low-cost sensors into state monitoring strategies alongside rigorous calibration and quality assurance protocols. High-resolution emission inventories at the district or sub-district level that incorporate seasonality and technology differentiation (e.g., kiln types, stove types, vehicle age distribution) are also needed to support robust source apportionment and scenario modeling.

Transboundary pollution complicates local control efforts because Bihar is both a source and a receptor within the IGP airshed. Modeling studies of interstate pollutant transport in India indicate that states such as Uttar Pradesh and West Bengal, along with emissions from the broader northwest IGP, significantly contribute to downwind levels of carbonaceous aerosols and ozone precursors over the eastern IGP states, including Bihar. Back-trajectory analyses in recent sensor-based studies suggest that 30–40% of winter air masses over Bihar originate from northwest India, carrying smoke from agricultural residue burning and urban-industrial plumes that add to local emissions and exacerbate winter smog. These findings highlight the need for regional airshed management frameworks with shared emission reduction targets, harmonized monitoring, and mechanisms for cross-border coordination, drawing on international examples from regions such as California's South Coast Air Basin and China's Beijing–Tianjin–Hebei cluster.

Climate change has introduced additional complexity through its influence on meteorology, rainfall patterns, and baseline temperatures in the IGP. Emerging analyses indicate a declining number of rainy days and altered monsoon behavior over the Gangetic Plain, which may reduce the frequency of wet scavenging events and prolong pollution episodes, particularly in the post-monsoon and winter seasons. High-resolution climate-air quality coupling studies in the Indo-Gangetic Basin (IGB) region report rising air temperatures and changes in boundary layer dynamics that can amplify secondary aerosol formation and ozone production, suggesting that future climate trajectories may worsen air quality if emissions are not substantially reduced. Future research in Bihar should therefore prioritize integrated assessments that jointly model emissions, meteorology, chemical transformation, and health outcomes under different development and climate scenarios, while also investigating the co-benefits of mitigation measures, such as clean energy transition, sustainable agriculture, and transport electrification.

CONCLUSION

Available evidence indicates that Bihar has emerged as a critical air pollution hotspot within the Indo-Gangetic Plain, with annual PM2.5 concentrations several-fold higher than the WHO guidelines and the Indian NAAQS in both urban and rural settings. The state's unique combination of dense population, extensive reliance on solid fuels, proliferating brick kilns, rapid yet uneven urbanization, and frequent winter inversion conditions creates a high exposure environment that imposes substantial health and economic burdens, estimated at nearly 2% of its GSDP in 2019. While NCAP-linked CAAPs, technological shifts in vehicles and brick kilns, and the expansion of monitoring infrastructure represent important steps, current measures remain insufficient to place Bihar on a trajectory consistent with safe air quality or sustainable development goals.

An integrated regional approach to air quality management is urgently needed, one that goes beyond city-centric measures to address rural emissions, agricultural burning, and transboundary transport within the broader IGP airshed. Priority actions include the rapid scaling of clean household energy access, stringent enforcement and technology upgrading in brick kilns and industrial sectors, accelerated deployment of public and non-motorized transport, and robust emission inventories and monitoring systems that inform evidence-based policymaking. Concurrently, investment in epidemiological research and health system strengthening in Bihar will be essential to better quantify and mitigate the health impacts of air pollution, particularly among children, the elderly, and outdoor workers, who bear a disproportionate share of exposure and risk. Given Bihar's demographic weight and strategic position in the IGP, success in reducing its air pollution burden would not only yield major local health and economic benefits but also contribute significantly to India's national and global commitments on air quality, climate, and sustainable development.

Acknowledgements

Gratitude is extended to Patliputra University, Patna, for providing all necessary facilities for research endeavors.

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