Journal of Environmental Management 405 (2026) 129784

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Cost-effective mitigation strategies for air quality management in Uttar Pradesh, India

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ARTICLE INFO

Keywords:
Air quality management
Cost-effective strategies
Emission inventory
Clean air plans
Airshed-based approach
Inter-state collaboration

ABSTRACT

Fine particulate matter ($PM_{2.5}$) pollution remains a major environmental and public health challenge across the Indo Gangetic Plain (IGP), one of the most densely populated and polluted regions in the world. Uttar Pradesh (UP), the most populous state in India, experiences persistently high $PM_{2.5}$ concentrations due to emissions from residential energy use, industry, transport, agriculture, and regional transport of pollutants. Despite recent policy initiatives such as the National Clean Air Programme, many urban and rural areas in the state continue to exceed National Ambient Air Quality Standards (NAAQS). This study evaluates cost-effective mitigation strategies for improving air quality in UP using the GAINS (Greenhouse gas–Air pollution Interactions and Synergies) model adapted for the IGP region. The analysis develops a region-specific emission inventory for UP for the baseline year 2020 and assesses future air quality outcomes to 2035 under current legislation and enhanced mitigation scenarios. The results show that in the base year 2020, approximately 44% of population-weighted $PM_{2.5}$ exposure in UP originates from sources outside the state, highlighting the importance of regional pollution transport. Secondary particulate formation contributes about 40% of total ambient $PM_{2.5}$ concentrations. Under the current policies, $PM_{2.5}$ exposure in 2035 remains well above national standards. Additional mitigation measures across residential, industrial, transport, and agricultural sectors can substantially reduce exposure levels at relatively low cost. The findings highlight the need for coordinated emission reductions across the IGP region and provide a basis for prioritizing cost-effective air quality interventions in UP.

1. Introduction

Ambient air pollution remains a critical global health concern, impacting populations across urban and rural areas, regardless of socioeconomic status. In 2023, exposure to fine particulate matter ($PM_{2.5}$) from ambient air pollution was estimated to cause 4.9 million premature deaths worldwide (HEI, 2025a), primarily through cardiovascular and respiratory diseases and cancer. South Asia has emerged as

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https://doi.org/10.1016/j.jenvman.2026.129784
Received 1 October 2025; Received in revised form 20 March 2026; Accepted 20 April 2026

a global hotspot for air pollution, with several of its urban centers exhibiting extremely high pollution levels, with 29 out of the 30 most polluted cities located in the region (IQAir, 2024; World Bank, 2023). Within South Asia, the Indo-Gangetic Plain (IGP[1]) experiences particularly severe air pollution, especially during the post-monsoon and winter seasons (Kumar et al., 2025; Ojha et al., 2020; Ravindra et al., 2020; Singh et al., 2021) due to a combination of high emissions and unfavorable meteorological conditions (Roozitalab et al., 2021).

Uttar Pradesh (UP), located at the core of the IGP, is India's most populous state, with over 240 million inhabitants (GoI, 2026). It spans 7.3% of India's landmass and is the second-largest state economy, with a GDP of approximately US$300 billion (IBEF, 2024). Its geographic position between the Himalayas and the Vindhya range influences regional climate conditions, leading to hot summers and frequent temperature inversions during winter that can aggravate air pollution episodes (Fig. S1). The IQAir (2024) database of the world's most polluted cities reports $PM_{2.5}$ concentrations for 23 cities in UP (Fig. S2). In all these cities, measured $PM_{2.5}$ levels significantly exceed both the World Health Organization (WHO) Air Quality Guideline of 5 $\mu g/m^3$ and the National Ambient Air Quality Standard (NAAQS) of 40 $\mu g/m^3$, with seven cities ranking among the world's 50 most polluted cities (IQAir, 2024).

Fourteen cities in UP are also classified as Non-Attainment Cities (NACs), having exceeded the NAAQS consistently over a five-year period and therefore requiring the development of local clean air action plans under the National Clean Air Programme (NCAP) (Sharma et al., 2023a). While implementation of these clean air action plans has led to measurable improvements in air quality in several cities since 2017, $PM_{2.5}$ concentrations in much of the region continue to pose serious health risks (Gopikrishnan and Kuttippurath, 2025; Bera et al., 2024; Kumar et al., 2024a). Recent assessments of NCAP progress also indicate that, although some Indian cities have reported declining pollution levels, many urban centers in the IGP continue to exceed NAAQS (HEI, 2025b; Manojkumar and Muruganandam, 2025). These persistent exceedances highlight the need for additional emission reductions across multiple sectors and underscore the importance of identifying cost-effective mitigation strategies that account for both local emissions and regional pollutant transport.

Air pollution research in UP has primarily concentrated on urban centers (Singh et al., 2025), particularly in cities like Lucknow (Chaudhary et al., 2008; Mumtaz et al., 2017), Kanpur (Sharma et al., 2004; Sharma and Maloo, 2005; Yadav and Ganguly, 2024) and Agra (Gogikar and Tyagi, 2016; Maji et al., 2017; Sah, 2023), recognizing their non-attainment status (Bera et al., 2024; Sharma et al., 2023a, 2023b). However, it is important to acknowledge the transboundary nature of air pollution. Urban areas are heavily impacted by emissions originating from surrounding semi-urban and rural areas, neighboring states, and even other countries (Luo et al., 2018; Pathak and Kuttippurath, 2024). For the broader IGP region, winter pollution source apportionment studies have identified residential, transportation, power plants, industrial combustion and processes, stubble and waste burning sectors as key contributors (Jat and Gurjar, 2021; Kumar et al., 2024b). While studies primarily focus on current pollution levels, there is limited attention to the impacts of policies like the NCAP (Gopikrishnan and Kuttippurath, 2024; Bera et al., 2024; Dholakia et al., 2013), future projections (Chowdhury et al., 2018), or strategies to achieve air quality standards (Chowdhury et al., 2019; Purohit et al., 2019). Stubble burning's post-monsoon pollution role is well-documented (Kumar et al., 2024b; Beig et al., 2020; Ravindra et al., 2019; Roozitalab et al., 2021), but other agricultural emissions, particularly ammonia, remain underexplored, despite the IGP being a global ammonia emission hotspot (Kuttippurath et al., 2020; Van Damme et al., 2018). Additionally, industrial emissions, vehicular exhaust, and natural dust from sources like the Arabian Peninsula and Thar Desert worsen pollution. Seasonal variations are shaped by changing emissions, monsoonal wet deposition, low mixing heights, and westerly winds, highlighting the complex interplay of sources and meteorological factors.

Despite ongoing policy efforts, a comprehensive and forward-looking strategy to achieve air quality standards in Uttar Pradesh is still lacking. In particular, there is a need to identify cost-effective mitigation pathways that integrate sectoral measures with regional coordination across the IGP (DoEFCC & World Bank, 2025). This study addresses this gap by applying the GAINS (Greenhouse gas–Air pollution Interactions and Synergies) model adapted for the IGP region to assess emission reduction strategies for Uttar Pradesh up to 2035, in particular those aimed at achieving the WHO Interim Target-1 (IT-1) of an annual average $PM_{2.5}$ concentration of 35 $\mu g/m^3$ by the year 2035.

We develop a region-specific emission inventory for the base year 2020 and evaluate air quality outcomes under current legislation and enhanced mitigation scenarios. IGP states have adopted Clean Air Action Plans incorporating airshed-based approaches, sector-specific interventions in agriculture, transport, and industry, city-level measures, and expanded monitoring networks (World Bank, 2024; Ghosh et al., 2023; Ganguly et al., 2020). Nevertheless, cross-border pollution and enforcement challenges continue to constrain air quality improvements (David et al., 2019; Dipoppa and Gulzar, 2024), highlighting the need for coordinated regional action. Our analysis identifies cost-effective measures across sectors, quantifies their impact on population exposure, and highlights the importance of coordinated action across state boundaries. By combining detailed emissions data with integrated assessment modeling, this study provides policy-relevant insights for designing effective air pollution control strategies in one of the world's most affected regions.

The structure of the paper is as follows: Section 2 provides a brief overview of key air pollution control policies and regulations. Section 3 outlines the modeling tools, scenarios, and data sources used in the study. Section 4 analyzes current air quality in UP, exploring its driving factors, population exposure, and pollutant dispersion. It also evaluates various pollution control scenarios from 2020 to 2035, assessing their impacts on air quality and the associated costs. Finally, Section 5 presents the conclusions.

2. Regulatory framework for air quality management in Uttar Pradesh

India's efforts to combat air pollution are coordinated at national and regional levels. The central government establishes regulatory frameworks such as NAAQS and the NCAP (MoEF, 2010; MoEFCC, 2019), while states, including Uttar Pradesh (UP), adapt these guidelines to local contexts through targeted action plans. At the national level, India has enacted a series of comprehensive legislative measures to address air pollution. The Air (Prevention and Control of Pollution) Act of 1981 introduced formal regulations, followed by the Environment (Protection) Act of 1986, which empowers the central government to set standards and implement regulations across multiple environmental sectors. This framework facilitated initiatives such as the 1995 mandate for unleaded petrol and catalytic converters in metropolitan areas, alongside complementary measures including the Motor Vehicle Act of 1988, the Municipal Solid Waste (Management and Handling) Rules of 2000, and the Noise Pollution (Regulation and Control) Rules of 2000 (Bhave and Kulkarni, 2015).

International commitments, including the 1992 United Nations Conference on Environment and Development (UNCED), influenced subsequent legislation. The National Environment Tribunal (NETA) Act of 1995 and the National Environment Appellate Authority (NEAA) Act of 1997 established judicial bodies for environmental violations and appeals, both of which were later superseded by the National Green Tribunal (NGT) Act of 2010. The NGT, grounded in Article 21 of the

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[1] Including Bihar, Chandigarh, Delhi, Haryana, Jharkhand, Punjab, Uttar Pradesh and West Bengal. Other neighboring states: Uttarakhand, Himachal Pradesh, Rajasthan, Madhya Pradesh and Chhattisgarh.

Constitution, expedites dispute resolution and upholds the right to a clean environment (Khandare, 2015). India's air quality governance is further reinforced through instruments such as the Environmental Impact Assessment (EIA) Notification of 1994, the Environment Pollution (Prevention and Control) Authority (EPCA) established by the Supreme Court in 1998, the Graded Response Action Plan (GRAP), and the NCAP introduced in 2019 (MoEFCC, 2019). In the National Capital Region (NCR), EPCA's air quality management functions were largely transferred to the Commission for Air Quality Management (CAQM) following an ordinance in 2020, enacted into law in 2021 (Gulia et al., 2022).

The Central Pollution Control Board (CPCB) introduced the NAAQS in 1981 for sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and Suspended Particulate Matter (SPM), later adding Respirable Particulate Matter (PM_{10}), lead (Pb), ammonia (NH_3), and carbon monoxide (CO) in 1994, with further revisions in 2009 (CPCB, 2009, 1994). NCAP targets a 20–30% reduction in PM_{10} and $PM_{2.5}$ by 2024 relative to 2017 levels, with a revised goal of 40% by 2026 (MoEFCC, 2025). The National Ambient Air Quality Monitoring Programme (NAMP), launched in 1987, has expanded from 411 manual stations in 2010 to 883 by 2023, while real-time monitoring, initiated in 2006 in Delhi, now covers 423 stations across 221 cities (CSE, 2023). As of 2024, India operates 1524 monitoring stations (966 manual, 558 continuous) across 550 cities, though challenges remain regarding station functionality and data quality (CSE, 2023; Srivastava et al., 2024; Manojkumar and Muruganandam, 2025).

At the state level, the Directorate of Environment (DoE) in UP formulates and implements policies for environmental protection, including airshed management strategies. The Uttar Pradesh Pollution Control Board (UPPCB) serves as the principal regulatory authority, overseeing permits, monitoring, public awareness campaigns, technology adoption, enforcement, and waste management. These coordinated efforts collectively aim to maintain a clean and healthy environment, with detailed state-level measures presented in Table S1 of the Supplementary Information (SI).

3. Methodology

3.1. The GAINS model

The Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model was used to estimate population exposure to $PM_{2.5}$, identify key sectoral and regional emission sources, and assess the cost-effectiveness of pollution control measures. As a decision-support tool, GAINS enables comparison of policy options based on their costs and benefits for air quality management (Amann et al., 2020). The model has been widely utilized across South Asia (Purohit et al., 2024; Mir et al., 2024; World Bank, 2023; Peszko et al., 2022) and ASEAN regions (UNEP/CCAC, 2019, 2025; World Bank, 2025a) to analyze air quality and climate policy. In India, GAINS has been used to evaluate mitigation strategies for achieving NAAQS (Purohit et al., 2019) and to assess the health benefits of cleaner air investments (Sanderson et al., 2013). In Pakistan and Nepal, the model has supported analyses of synergies between air pollution control and climate change mitigation (Mir et al., 2022; Purohit et al., 2013; World Bank, 2025b). Additional applications include studies on households contributions to air pollution in India (Rao et al., 2021), health impacts of $PM_{2.5}$ and ozone exposure in northern India (Karambelas et al., 2018) and urban air quality management in Delhi (Amann et al., 2017; Bhanarkar et al., 2018; Dholakia et al., 2013) and Kolkata (Majumdar et al., 2020).

This research employed the IGP specific version of the model, GAINS-IGP, to identify cost-effective strategies for reducing $PM_{2.5}$ exposure in UP. GAINS is an integrated assessment model that combines detailed emissions inventories with information on control technologies to evaluate air pollution mitigation options (see Fig. S3). We constructed emissions scenarios for over 400 anthropogenic sources for the years 2020 and 2035, incorporating projections based on socio-economic developments. To capture regional pollution dynamics, the analysis included emissions from 31 regions (mostly provinces or states) from South Asia (World Bank, 2023), rather than limiting the scope to UP alone. The study focused on both primary $PM_{2.5}$ emissions and its secondary precursors, including SO_2, NO_x, NH_3, and non-methane volatile organic compounds (VOCs). Further details of the GAINS modeling framework are provided in Section S1 of the SI, and the GAINS-IGP interface can be accessed at: http://gains.iiasa.ac.at/

The emissions of pollutants were estimated based on the combination of activity levels, emission factors, and the implementation of control technologies. The GAINS model estimates pollutant emissions using the following equation, which integrates activity levels, uncontrolled emission factors, efficiencies of control technologies, and their application rates. The emissions for a given pollutant were calculated as:

$$EM_{i,p} = \sum\nolimits_{k} \sum\nolimits_{m} A_{i,k}\, EF_{i,k,m,p}\, X_{i,k,m,p} \tag{1}$$

where i represents the region, k the type of activity, m the abatement or control measure, and p the specific pollutant. Here, $EM_{i,p}$ is the total emission of pollutant p in region i, $A_{i,k}$ is the level of activity k, $EF_{i,k,m,p}$ is the emission factor for pollutant p after applying measure m, and $X_{i,k,m,p}$ represents the fraction of activity k to which control measure m is applied.

The activity data underlying the emissions estimates were primarily derived from publicly available sources, as described in section S3 of the Supplementary Information (SI). In cases where such data is unavailable, estimates were provided by the Department of Environment, Forest and Climate Change (DoEFCC), Government of Uttar Pradesh. Emission factors were predominantly based on localized measurements that accurately reflect source-specific conditions within the region, particularly within the South Asian context. The GAINS-IGP model incorporates several hundred established emission control technologies (see Section S1). The removal efficiencies associated with these measures were sourced from global literature, with adjustments made to reflect the specific conditions in UP. The implementation rates of each measure represent the proportion of total relevant activities to which the measure is applied at a given time. Total emissions for each source category were spatially allocated using appropriate proxies (location data for major point sources, population density maps, road network data, land use patterns, and agricultural statistics). Temporal variations in emissions, including daily and seasonal patterns, as well as the release heights for each source category, were also accounted for. Natural emission sources were included in the atmospheric model calculations with the EMEP model (Simpson et al., 2012). These natural sources were assumed to remain constant across different emission scenarios.

Using emission fields for all $PM_{2.5}$ precursor pollutants, annual average $PM_{2.5}$ concentrations in ambient air were calculated across the IGP at a spatial resolution of $0.1^\circ \times 0.1^\circ$ (roughly 10 km × 10 km). Atmospheric calculations have been described by (Amann et al., 2020; Purohit et al., 2024). The GAINS-IGP framework applies reduced-form source-receptor relationships developed from the EMEP atmospheric chemistry transport model, which accounts for variations in emission release heights across different source types (Simpson et al., 2012). The full-scale EMEP model simulations were conducted using hourly meteorological data for the year 2018 specific to the IGP region. These simulations also incorporated the characteristic temporal profiles, both seasonal and diurnal, for each emission category. Secondary $PM_{2.5}$ formation and its atmospheric transport, resulting from precursor emissions such as SO_2, NO_x, NH_3, and VOCs, were simulated at a coarser resolution of $0.5^\circ \times 0.5^\circ$ in both latitude and longitude. To assess human exposure, $PM_{2.5}$ concentration values for the study region were combined with gridded population data to produce a population-weighted exposure metric. This was done by summing the products of average $PM_{2.5}$ levels and the population count in each grid cell. Modeled $PM_{2.5}$ concentrations were validated using observational data from 53 continuous ambient air quality monitoring stations and 26 manual monitoring locations within the UP. A comparative analysis between observed measurements and GAINS model outputs yielded $R^2 = 0.638$ and RMSE = 16.612. These values indicate a moderate level of agreement between modeled and observed concentrations for UP and are within the range commonly reported for regional air quality modeling studies. A focused evaluation for UP is provided in Fig. S4.

We applied the stand-alone GAINS optimization module to identify the most cost-effective strategies for achieving specific air quality targets, particularly reductions in pollutant concentrations (Wagner et al., 2013). Cost estimates for individual control options were derived from a combination of international and Indian sources, including published literature and market data, and are then adapted to the local context of UP by factoring in regional wage levels and purchasing power parity. Additional details on the GAINS cost framework are provided in Section S2 of the SI. To evaluate cost-effectiveness, the analysis calculates the cost per unit reduction in population-weighted exposure, for example, the cost per μg/m^3 decrease in $PM_{2.5}$ concentrations. A comprehensive description of the methodology, including the equations used, is available in Wagner et al. (2013).

Building on the modeling framework described above, the following section outlines the emission scenarios and future activity projections implemented in GAINS-IGP to evaluate potential trajectories of $PM_{2.5}$ emissions and population exposure in UP.

3.2. *Emission scenarios and future projections*

The GAINS-IGP assessment for UP is grounded in the recently developed cost-effective mitigation strategies for South Asia (Purohit et al., 2024) and has been refined using the most up-to-date local statistical data available for the state. Most of the activity data corresponds to the years 2019 or 2020, while some sectors rely on 2018 figures due to differences in the availability and reporting frequency of official statistics across data sources. These local data sets encompass a wide range of sectors, including household fuel use in both urban and rural areas, fuel consumption across power generation, industrial and transport sectors, industrial processes, agricultural residue burning, and waste management practices. Additional information on the sources of activity data is available in section S3 of the SI.

To project future trends through 2035, the GAINS-IGP model extends current source contributions by accounting for anticipated socio-economic developments that influence emission-related activities, as well as existing environmental regulations. Sector-specific modeling approaches are employed to forecast activity levels across domains such as energy, agriculture, waste, and transport. While the model does not assume the introduction of new energy policies that alter fuel shares, it does incorporate expected gains in energy efficiency resulting from ongoing technological advancements, such as the deployment of modern coal-based power plants. The model assesses a wide range of emission control measures to identify cost-effective strategies for air quality improvement. It estimates emissions of $PM_{2.5}$ precursors for the year 2020 under the Current Legislation (CLE) scenario and quantifies their impact on population-weighted $PM_{2.5}$ exposure in UP. Additional information on the legislative context and abatement options under the CLE scenario is available in Section S4 of the SI.

For the year 2035, three alternative scenarios are applied to evaluate the effectiveness of different control strategies in reducing emissions and exposure. The analysis highlights the extent of air quality improvements achievable through full policy implementation relative to a counterfactual baseline (FLE) and prioritizes control measures based on cost-effectiveness. It further considers both local interventions and regionally coordinated actions across the IGP, while estimating the implementation costs associated with each scenario. This study evaluates three air quality management strategies represented by alternative emission scenarios.

The *Current Legislation (CLE) scenario* projects $PM_{2.5}$ concentrations in 2035 assuming full enforcement of all air quality regulations in force as of 2020 and uses 2020 as the base year for emissions estimates. It serves as the reference case against which alternative mitigation strategies are assessed. The *Frozen Legislation (FLE) scenario* represents a counterfactual scenario in which no new air pollution control policies are introduced after 2015, illustrating the likely evolution of emissions and population exposure under continued economic growth without additional regulatory intervention. Emission projections are generated using the GAINS model, which attributes changes in emissions to activity growth, fuel consumption, industrial processes, livestock, and end-of-pipe abatement measures. To reflect uncertainty in the evolution of household energy use, two variants are considered: (i) FLE, where policies and technology penetration remain fixed at 2015 levels with no further penetration of cleaner fuels, and (ii) FLE-CF, where policies remain unchanged, but the clean-fuel transition embedded in the 2015 framework continues. Comparing these variants helps isolate the effects of policy stagnation from structural changes in household fuel use. The *Coordinated Action Scenario (CAS)* builds on the air pollution control measures included in the CLE scenario and evaluates the impact of widely recognized low-cost interventions implemented across the IGP region. This scenario explores the potential to achieve the WHO IT-1 of 35 μg/m^3 by 2035, through coordinated emission control measures across the entire IGP airshed, including UP.

4. Results

The following sub-sections present the results of current and future contributions of various pollution sources contributing to $PM_{2.5}$ levels in UP under different scenarios and propose cost-effective strategies to meet the WHO Interim Target 1 of 35 μg/m^3 within the state using the GAINS modeling framework.

4.1. *Apportionment of local and regional sources*

Using the methodology described above, sectoral and geographic contributions to $PM_{2.5}$ concentrations in UP were estimated and are presented in Fig. 1. In 2020, the population-weighted average $PM_{2.5}$ exposure in UP was 65.4 μg/m^3. Of this, 36.9 μg/m^3 originated within the state, 21.9 μg/m^3 came from sources outside UP's jurisdiction, and 6.7 μg/m^3 was attributed to natural sources (including soil dust and sea salt) as shown in Fig. 1(a). Within UP, the residential sector is the dominant contributor, accounting for 42% of $PM_{2.5}$ exposure, largely due to the use of solid fuels in traditional cookstoves. This is followed by manure and fertilizer use (17.4%), industrial combustion and processes, including brick kilns (11.2%), transport (8.9%), road and construction dust (8.0%), agricultural residue burning (6.9%), municipal waste (3%) and power plants (2.6%).

From outside UP, neighboring IGP states, such as Bihar, Delhi, Haryana, and Jharkhand contribute 13.2%, followed by 5.8% from other IGP states, 3.6% from non-IGP neighboring states, 1.4% from other Indian regions, and 9.3% from transboundary sources, primarily Pakistan. As further illustrated in Fig. 1(a)–a comprehensive analysis across the IGP airshed shows that the residential sector remains the largest contributor to $PM_{2.5}$ exposure in UP (30.6%), followed by manure and fertilizer use (13.3%), industrial combustion and processes, including brick kilns (12.7%), transport (11.1%), agricultural residue burning (6.5%), road and construction dust (6.0%), power generation (5.4%), and municipal waste management (4.2%)

Fig. 1(b) shows the sectoral contributions to primary PM and the total contribution of secondary PM to the population-weighted average $PM_{2.5}$ exposure in UP. Approximately 24.1% of primary $PM_{2.5}$ in UP originates from neighboring and other Indian states, with significant inputs from upwind regions such as Haryana, Delhi, and Punjab. In these areas, residential emissions are comparatively lower because the use of solid fuels is reduced, especially in Delhi and parts of northwest India. Contributions from more distant sources are largely due to secondary $PM_{2.5}$, which forms in the atmosphere from precursor emissions such as

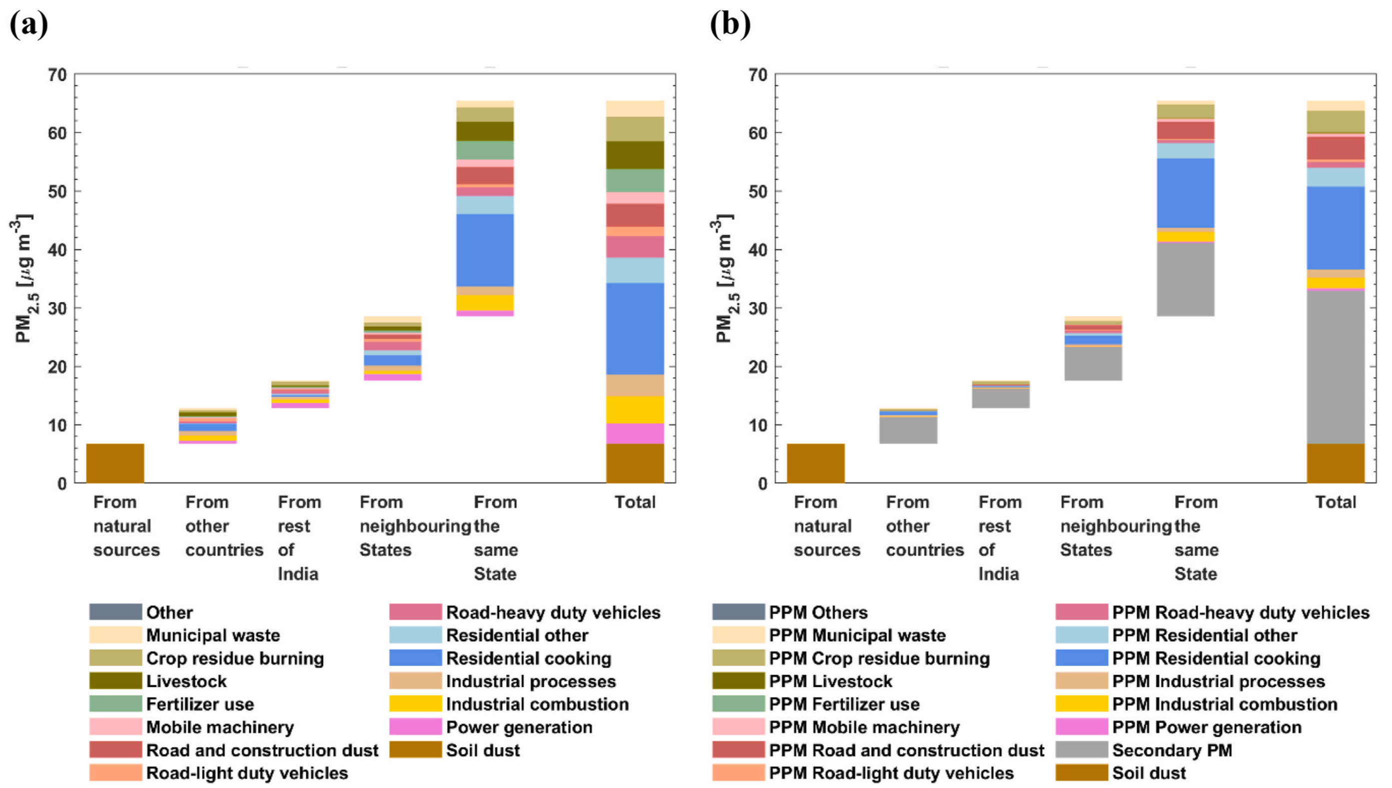

Fig. 1. Source apportionment of population-weighted $PM_{2.5}$ concentrations in UP for 2020: (a) Contributions of different geographic origins to $PM_{2.5}$ exposure, and (b) Sectoral contributions to primary $PM_{2.5}$, which is emitted directly from sources, and the total contribution of secondary $PM_{2.5}$, which forms in the atmosphere through chemical reactions of precursor gases such as SO_2, NO_x, NH_3, and VOCs.

sulfur dioxide and nitrogen oxides from coal combustion and industrial activities, as well as ammonia from fertilizer use in agriculture and livestock production. Additionally, transboundary pollution from regions outside India, especially upwind areas in Pakistan, accounts for approximately 7% of $PM_{2.5}$ in UP. Fig. 1(b) highlights the critical role of secondary $PM_{2.5}$, which forms in the atmosphere through chemical reactions involving precursor gases such as SO_2, NO_x, NH_3, and VOCs. It indicates that approximately 40% of $PM_{2.5}$ exposure in UP is attributable to secondary $PM_{2.5}$, with about 48% originating within the state and the remaining 52% from sources outside UP. The substantial presence of secondary $PM_{2.5}$ helps explain the disproportionate influence of certain sectors, on overall $PM_{2.5}$ concentrations, despite their relatively low direct (primary) emissions.

4.2. Air pollution scenarios for 2035

The assessment above indicates that $PM_{2.5}$ levels in UP significantly exceed both national and global air quality benchmarks, contributing to serious health risks. Although residential sector activities are the main source of emissions, other sectors, such as transportation, along with the formation of secondary particles in the atmosphere, also play a substantial role in high pollution levels. To develop effective strategies for improving future air quality and aligning with established standards, we analyze the influence of existing policies on $PM_{2.5}$ concentrations, consider the scope for further emission reductions within UP, and examine how these efforts might complement broader interventions across the IGP region.

4.2.1. Baseline projections for 2035

Ongoing social and economic development is expected to shift the relative contributions of different sectors to population exposure while revealing the longer-term effects of recent policies and measures. To account for these changes, this analysis incorporates a baseline projection, also known as the CLE scenario, for the year 2035, outlining anticipated trends in emissions and air quality. Under this scenario, the state's population is projected to grow at an average annual growth rate of 0.8%, leading to a 13% increase by 2035 compared to 2020 levels (IEA, 2024). Concurrently, per capita GDP is expected to rise by 5.4% each year, resulting in a nearly 2.5-fold expansion of overall economic output. This economic growth is projected to drive a near doubling of primary energy consumption between 2020 and 2035, accompanied by a marked shift toward cleaner energy sources.

Fig. 2 presents the projected trajectories of key macroeconomic indicators, including population, GDP, GDP per capita, and energy consumption, under the CLE scenario from 2020 to 2035. These developments are important because changes in energy demand and fuel composition strongly influence emissions of primary $PM_{2.5}$ and its precursor gases, thereby affecting population exposure to air pollution. During this period, per capita energy consumption is expected to rise by 65%, while the energy intensity of GDP is projected to decline by 25%, indicating improved energy efficiency. A notable reduction in biomass use is anticipated, largely due to clean cooking initiatives under the *Ujjwala* scheme, which is expected to lower emissions of primary $PM_{2.5}$ from the residential sector. At the same time, renewable energy sources such as wind, solar, and hydropower are projected to expand substantially, by approximately fifty times, while nuclear capacity is projected to double, contributing to lower emissions from electricity generation. However, consumption of oil and natural gas is also projected to increase by factors of 1.2 and 2.6, respectively, which may influence emissions of $PM_{2.5}$ precursors depending on sectoral use and the effectiveness of emission control measures.

The baseline projections follow the current legislation, which refers the full implementation of sector-specific policies in force as of 2020 across the energy, power generation, industry, transport, agriculture, waste, and residential and commercial sectors. The scenario assumes widespread adoption of emission control measures, including Bharat

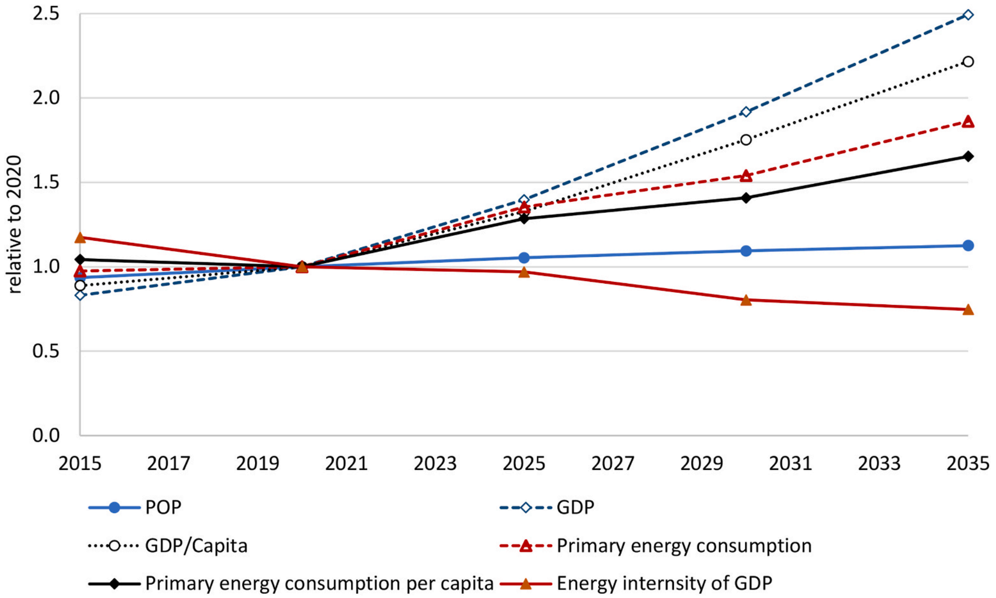

Fig. 2. Trend of macro-economic drivers (i.e., population, GDP, GDP/capita) and energy use under the baseline scenario (2020-2035).
Sources: *GAINS model*

Stage VI standards for most road vehicles, particulate and flue gas desulfurization controls at large coal-fired power plants, a substantial transition to clean cooking fuels in households, and the deployment of particulate controls in industry alongside the conversion of brick kilns to cleaner technologies. A detailed list of the air pollution control measures assumed for 2035 under CLE is provided in Table S11. To evaluate the effectiveness of these policies, a Frozen Legislation (FLE) scenario was also developed, which assumes no new measures beyond those in place in 2015. The contrast between the CLE and FLE shows how regulation helps decouple emissions from economic growth (see Fig. S5).

The baseline CLE scenario projects substantial reductions in several key air pollutants by 2035, despite strong economic growth. SO_2 emissions are expected to decline by 51%, reflecting effective flue gas desulfurization in large coal-fired power plants and cleaner industrial fuels. Primary $PM_{2.5}$ emissions fall modestly by 7% driven by the adoption of advanced vehicle standards, cleaner cookstoves, and particulate controls in industry. VOC emissions decreased by 11% due to improvements in industrial processes and reductions in residential biomass use. In contrast, emissions of NO_x and NH_3 rise by 37% and 15%, respectively, though their growth is slower than that of GDP, reflecting partial decoupling under CLE (see Fig. S5a). In contrast, under the FLE scenario, which assumes no additional measures beyond 2015, emissions increase sharply: SO_2 rises by 127%, NO_x by 129%, and $PM_{2.5}$ by 43% (Fig. S5b). This comparison highlights the critical role of policy interventions in limiting pollutant growth despite rapid economic and energy expansion.

By 2035, industrial-sector measures, including interventions in brick kilns, are projected to deliver nearly one third of total reductions in primary $PM_{2.5}$ emissions. Residential and commercial initiatives, such as the *Ujjwala* scheme promoting a shift from biomass to cleaner cooking options like LPG and induction stoves, are projected to deliver about one-quarter of the reductions. Municipal solid waste regulations add a further 9%. For SO_2, more than half of the anticipated reductions arise from the power sector, about one-third from industrial measures and the remainder from transport. For NO_x, over half the reductions from the implementation of Bharat Stage (BS) standards for vehicles and non-road mobile equipment. The rest are shared relatively evenly among controls on industrial combustion and processes, power generation, and other sources – including municipal waste, residential energy use, and agricultural.

The divergence between the two emission pathways is evident in projected $PM_{2.5}$ exposure. Under the Frozen Legislation (FLE) scenario, where economic growth continues without additional controls, $PM_{2.5}$ exposure in UP is expected to rise sharply between 2020 and 2035. This increase would be driven largely by emissions from industry, road and construction dust, non-road mobile machinery, and inadequate waste management. As illustrated in Fig. 3, average population-weighted $PM_{2.5}$ exposure would reach ~96 μg/m^3, about 50% higher than 2020 baseline of 65 μg/m^3. Introducing clean fuel policies under the FLE-CF variant offsets this increase partially and result in an exposure level of 80.4 μg/m^3. This comparison underscores the significant role of clean fuel policies in protecting public health: even the continuation of 2015 measures could substantially curb the growth of harmful air pollution. Note that current legislation implemented between 2020 and 2035 will lead to a de facto stabilization of exposure, despite sustained GDP growth (Fig. S6a–b). Full implementation of these policies and regulations is expected to cut average $PM_{2.5}$ exposure by 28.5 μg/m^3 relative to FLE, reducing levels from 96 μg/m^3 to 67.5 μg/m^3.

As with overall emissions reductions, efforts to reduce reliance on solid biomass for cooking, particularly through clean cooking programs, are projected to substantially lower exposure from the emissions in the residential sector. These gains, however, are partly offset by rising emissions from fertilizer use. Transboundary pollution inflows were held constant in the analysis, reflecting a methodological simplification to isolate the impacts of local and regional sources while assuming similar policy trajectories across the IGP airshed. Overall, 44% of total $PM_{2.5}$ exposure in UP originates from sources outside the state and from natural dust. Within this context, the residential sector - both within and beyond UP's borders - accounts for roughly one-third of total exposure. Other major contributors include brick kilns and small-scale industries, fertilizer use and livestock, and transport, each responsible for about 7–17% of the total burden.

Fig. 4 shows the spatial distribution of annual average $PM_{2.5}$ concentrations in UP, as estimated by the GAINS-IGP model. These values reflect the combined influence of local emission sources, atmospheric transport, and the formation of secondary $PM_{2.5}$. In 2020, the population-weighted average was ~65 μg/m^3, with nearly all districts exceeding the NAAQS limit of 40 μg/m^3. The highest concentrations were in NCR districts Ghaziabad and Noida (>80 μg/m^3), while western (Meerut, Mathura, Aligarh), eastern (Gorakhpur, Azamgarh) districts,

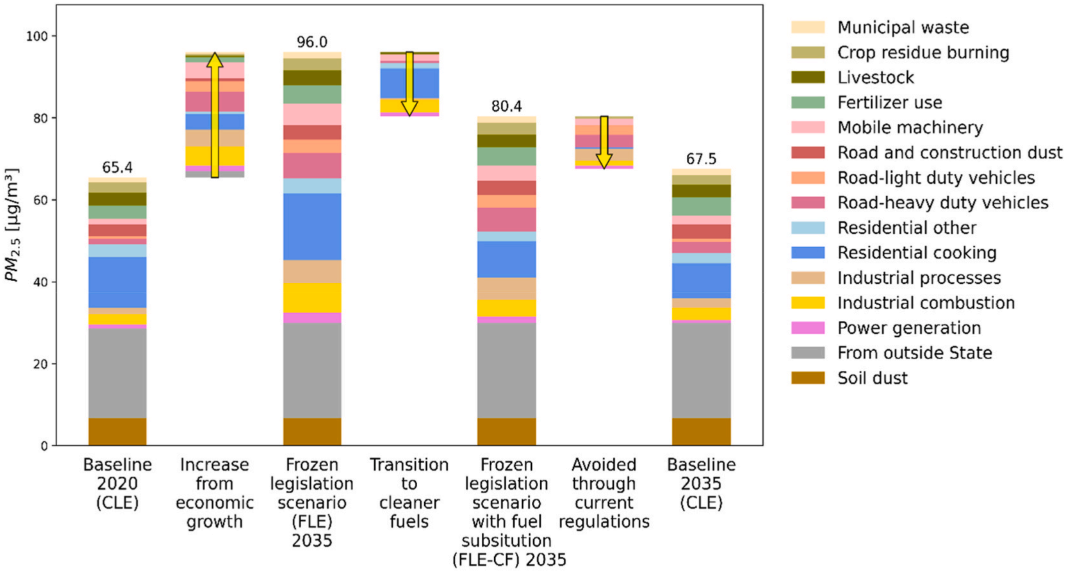

Fig. 3. Source apportionment of population exposure to $PM_{2.5}$ in UP 2020-2035, with and without implementation of current policies.

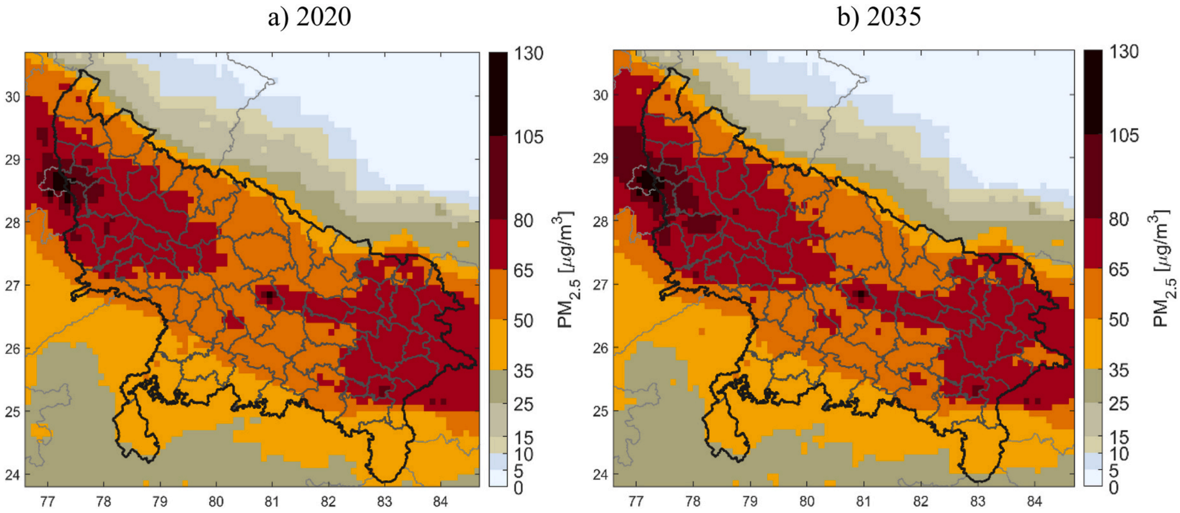

Fig. 4. Spatial distribution of annual mean $PM_{2.5}$ concentration in the CLE scenario in Uttar Pradesh, a) 2020; and b) 2035.

and Lucknow ranged 65–80 μg/m^3. Central UP largely fell between 50 and 65 μg/m^3, and southern districts (Jhansi, Lalitpur, Chitrakoot) were 35–50 μg/m^3. By 2035, hotspots persist in western and eastern UP, though central and southern regions show moderate improvements. Without regional cooperation, cross-border pollution may keep western UP above 40 μg/m^3, highlighting the need for coordinated action to protect public health across the airshed.

4.2.2. Pathways to further reductions of $PM_{2.5}$ exposure in Uttar Pradesh

There remains substantial scope for further improving air quality in UP through the adoption of well-established measures that have been proven effective in other parts of the world. This section assesses the additional potential for reducing $PM_{2.5}$ exposure by incorporating these measures, as part of a broader effort to identify viable pathways for achieving the NAAQS within the next decade. Full implementation of existing policies and regulations is projected to lower average $PM_{2.5}$ exposure in UP by 28.5 μg/m^3 (Fig. 5, blue bars). Beyond this, adoption of widely implemented measures could deliver further significant reductions in emissions of $PM_{2.5}$ precursors (Fig. 5, orange bars).

We have identified eight common high-impact measures for the entire IGP region, using the GAINS optimization tool under a Coordinated Action Scenario (CAS) as shown in Box 1 below. Collectively, these strategies could substantially reduce $PM_{2.5}$ exposure in UP beyond the reductions expected under current legislation, thereby contributing significantly to progress toward achieving the NAAQS. If implemented unilaterally in UP, these measures could reduce average $PM_{2.5}$ exposure from 67.5 μg/m^3 to about 41 μg/m^3 by 2035 (Fig. 6). However, even with full deployment, exposure would remain just above (41 μg/m^3) the NAAQS target of 40 μg/m^3. Importantly, more than three-quarters of the residual $PM_{2.5}$ exposure in 2035 would originate from sources outside UP. Without additional emission controls in neighboring states, inflows from other regions and natural sources are projected to contribute roughly 30 μg/m^3, while UP's own contribution would fall to just 11 μg/m^3.

Regional cooperation significantly alters projected $PM_{2.5}$ exposure in UP. Under the *Coordinated Action Scenario (CAS)*, if a coordinated set of widely implemented mitigation measures as outlined in Box 1 were implemented across all the IGP States, the inflow of $PM_{2.5}$ pollution into UP would decline by 7.5 μg/m^3. This would lower average population-weighted $PM_{2.5}$ exposure in the state from 67.5 μg/m^3 (baseline under

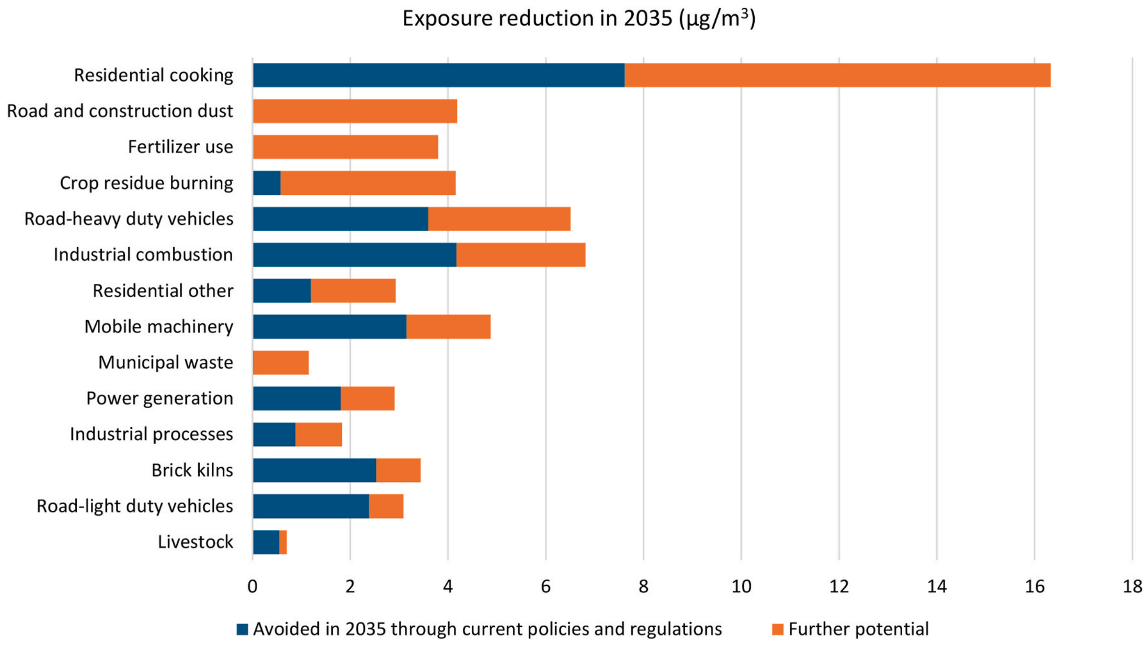

Fig. 5. $PM_{2.5}$ exposure reductions in UP in 2035 emerging from the possible emission controls in the various economic sectors within UP (ranked by decreasing potentials for further exposure reductions).

Box 1

High-Impact Measures for Reducing $PM_{2.5}$ Exposure in the Indo-Gangetic Plain (CAS Scenario)

Using the GAINS optimization framework, eight widely implemented measures were identified that together account for ~87% of the additional $PM_{2.5}$ exposure reduction (~30 $\mu g/m^3$) beyond current legislation.

Measure	Estimated reduction in UP ($\mu g/m^3$)
1) Clean cooking and heating (replace solid fuels with electricity, LPG, or natural gas)	8.7
2) Reduction of construction and road dust	4.2
3) Improved urea fertilizer efficiency	3.8
4) Elimination of open crop-residue burning	3.6
5) PM controls on industrial boilers and compliance of brick kilns	3.5
6) Enforcement of emission standards for heavy-duty diesel vehicles	2.9
7) Emission regulation for non-road mobile machinery	1.7
8) Low-emission municipal solid waste management	1.1

current legislation, CLE) to approximately 60 $\mu g/m^3$, even without additional local measures. With coordinated efforts, UP could reach 35 $\mu g/m^3$ by relying on only a subset of the full range of interventions (Fig. 6), thereby achieving about 87% of the maximum potential reduction. Further cooperation across the airshed would lower background levels even more, reducing reliance on the most costly or complex measures within UP and generating significant cost savings.

This cooperative pathway underscores the transformative potential of regional strategies for air quality management. Given that neighboring states in the IGP face similar air quality challenges, parallel mitigation efforts are both likely and mutually beneficial. Implementing a region-wide coordinated strategy enables UP to meet the WHO Interim Target 1 of 35 $\mu g/m^3$ more efficiently while providing shared health and environmental benefits across the airshed.

The analysis underscores the benefits of a regional cooperative approach across the IGP. If a common set of mitigation measures were implemented across the IGP by 2035, UP would experience a 7.5 $\mu g/m^3$ reduction in cross-border $PM_{2.5}$ inflow. This would lower the baseline exposure in the cost curve (Fig. 7) from 67.5 $\mu g/m^3$ to 60 $\mu g/m^3$ (Fig. 7, red line). Such coordination would not only enable UP to meet the NAAQS target but would also generate air quality improvements across neighboring states, demonstrating the mutual gains of regional cooperation.

4.3. *Cost-effective strategies for reduction of $PM_{2.5}$ exposure*

To inform evidence-based policymaking on the cost-effectiveness of interventions, the GAINS-IGP framework evaluates integrated, multi-sectoral strategies that achieve predefined air quality targets at the lowest possible economic cost. This assessment accounts for both the financial costs required to implement emission control measures and their effectiveness in reducing population exposure to $PM_{2.5}$ in UP. While targeting the largest emission sources may appear impactful, such approaches often prove more expensive than strategies optimized for cost-effectiveness. To identify the most efficient options, this study quantified both the implementation cost and the associated reduction in

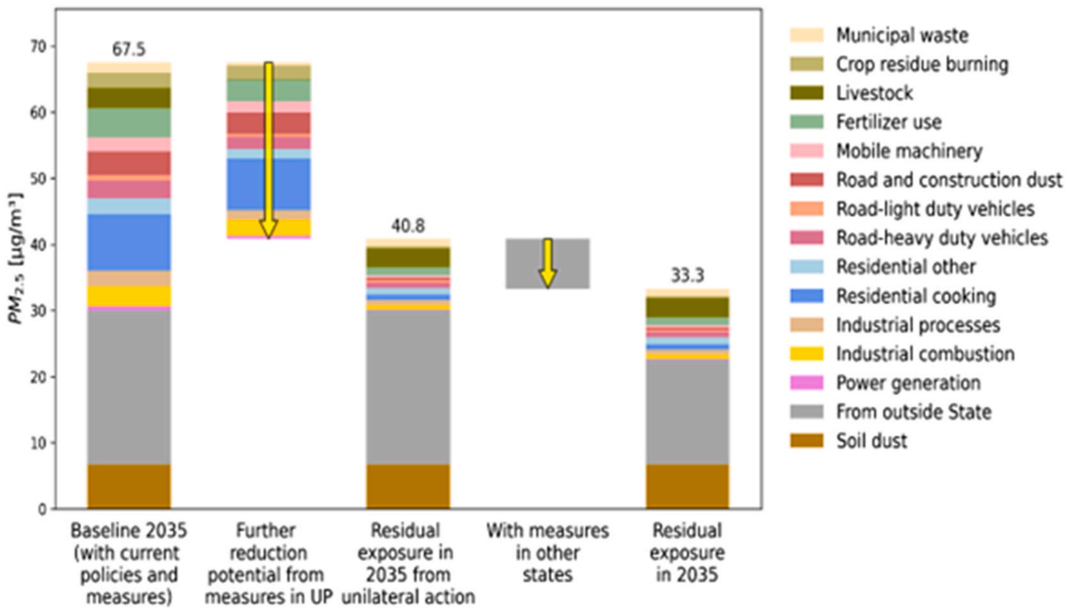

Fig. 6. $PM_{2.5}$ exposure reductions in UP offered by further measures in UP and by the common set of measures in other IGP States as outlined in Box 1.

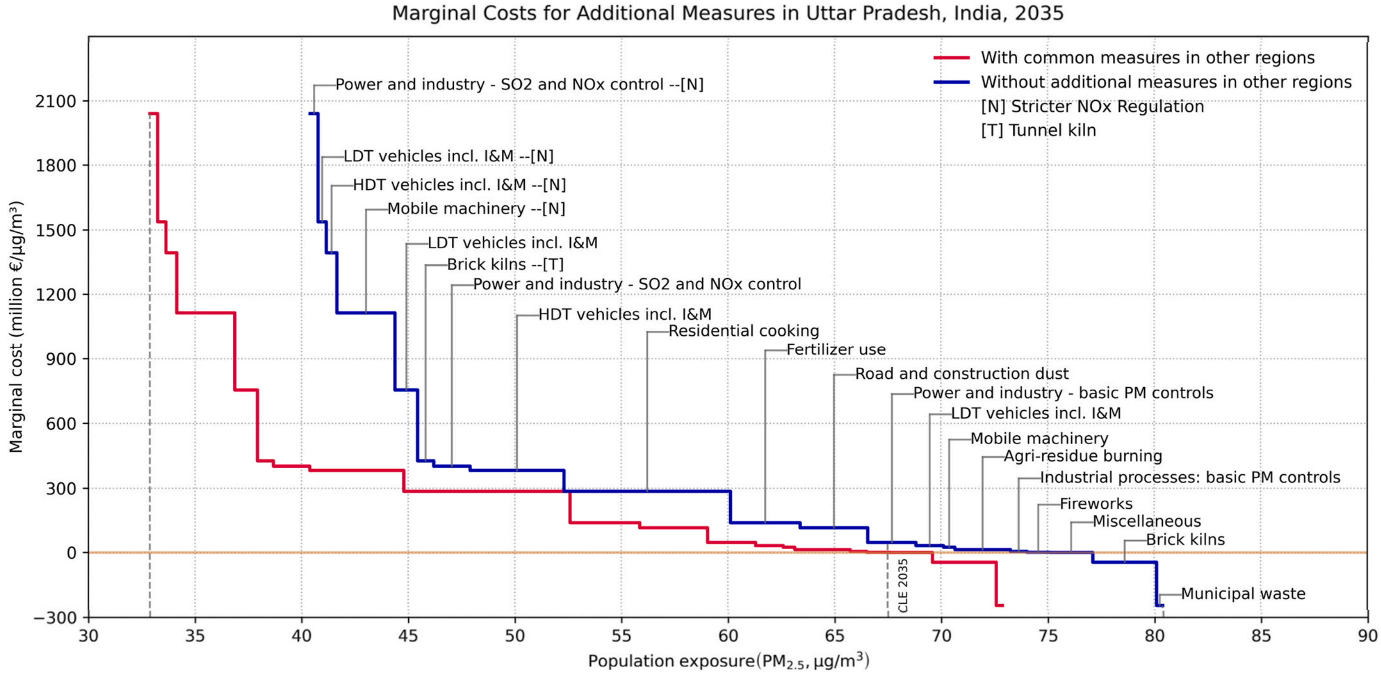

Fig. 7. Marginal cost curve for reducing population-weighted $PM_{2.5}$ exposure UP. The *blue line* represents unilateral action in UP, showing the cost-effectiveness of implementing emission reduction measures within the state alone. The *red line* represents coordinated implementation of the same set of mitigation measures across all IGP states, reflecting regional cooperation. The x-axis shows population-weighted $PM_{2.5}$ exposure (μg/m^3), while the y-axis indicates the marginal cost (€ million) to achieve a 1 μg/m^3 reduction in exposure. Each horizontal segment corresponds to a category of interventions, with the segment height reflecting the associated marginal cost. This visualization illustrates how regional coordination can reduce both $PM_{2.5}$ exposure and implementation costs relative to unilateral measures.

population exposure, expressed as the expenditure required to achieve a further 1 μg/m^3 decrease in exposure across UP. The measures are then ranked according to their marginal cost. Fig. 7 illustrates the resulting marginal cost curve (blue line), generated using the GAINS optimization tool. The x-axis (Fig. 7) shows the resulting population exposure to $PM_{2.5}$ (from all IGP sources), while the y-axis represents marginal costs. The curve summarizes over 300 cost-effective emission reduction measures, grouped into 20 categories, and represents the most cost-efficient combination of interventions.

The cost curve starts at an average $PM_{2.5}$ concentration of 80.4 μg/m^3, corresponding to the FLE-CF scenario (Fig. 3), which serves as a baseline for assessing the costs and benefits of further emission reductions. Fuel substitution costs are not included, as they fall outside the GAINS optimization framework. Each horizontal segment of the curve represents the reduction potential of a specific category of measures, while its height indicates the associated marginal cost (Fig. 7). Notably, several measures achieve reductions of about 3 μg/m^3 at negative costs - meaning they both lower pollution and yield net economic savings.

Examples include municipal waste separation with energy recovery and upgrading brick kilns with energy-efficient technologies. Beyond these cost-saving options, further reductions can be achieved across a range of costs.

Lowest cost tier (*<€25 million per* $1 \mu g/m^3$ *reduction*): Exposure can be reduced by up to 7 $\mu g/m^3$ using highly cost-effective interventions. This tier includes eliminating agricultural residue burning, introducing basic PM controls in power plants and industries, promoting low-sulfur diesel in non-road machinery (e.g., tractors, water pumps, construction equipment, locomotives, and ships), banning firecrackers, supporting electric cremation, and enhancing rural solid waste management.

Low-to-medium cost tier (*€25–150 million per* $1 \mu g/m^3$ *reduction*): Additional reductions of approximately 10 $\mu g/m^3$ can be achieved through measures such as improving urea fertilizer efficiency, mitigating road dust resuspension through paving and street cleaning, extending basic PM controls in industry, and tightening inspection and maintenance requirements for light-duty trucks. These interventions represent a balance of moderate cost and substantial exposure reduction.

Medium-cost tier (*€150–450 million per* $1 \mu g/m^3$ *reduction*): A further 15 $\mu g/m^3$ reduction can be realized by deploying higher-cost strategies including universal access to clean cooking energy (electric induction stoves, LPG, natural gas, or solar-powered alternatives) and installing filters in commercial kitchens. Further gains can be made by strengthening inspection and maintenance for heavy-duty trucks, introducing effective SO_2 and NO_x controls in power plants and industrial facilities, and adopting advanced brick kiln technologies, such as tunnel kilns.

High-cost tier (*> €700 million per* $1 \mu g/m^3$ *reduction*): Additional reductions are obtained through advanced interventions, such as stringent NO_x controls in mobile machinery, more stringent NO_x controls in power plants and industrial facilities and further tightening of inspection and maintenance standards for both light- and heavy-duty trucks. While these measures yield substantial reductions, they involve higher implementation costs.

In practical terms, the marginal cost curve identifies which interventions provide the largest reductions per unit cost, highlighting opportunities for measures that both improve air quality and generate economic benefits. Lower-cost measures deliver immediate gains, while higher-cost interventions enable further reductions where necessary. Regional coordination reduces dependence on the most expensive actions, making it feasible for UP to meet air quality standards efficiently and cost-effectively while generating shared benefits across the IGP airshed.

Although external interventions do not change the costs or reduction potential of measures implemented within UP, regional cooperation can significantly ease the state's challenge in meeting exposure target by reducing reliance on the most expensive measures. Under unilateral action, UP alone cannot achieve the NAAQS target of 40 $\mu g/m^3$ without incurring prohibitively high annual costs (Fig. S7, blue line). In contrast, coordinated implementation of a common set of mitigation measures across the IGP enables the state to reach the same target at a substantially lower annual cost of approximately €5 billion (red line and boxed area in Fig. S7). These cooperative strategies not only reduce costs but also deliver air quality improvements across neighboring states, enhancing overall cost-effectiveness. The analysis demonstrates that regional collaboration makes attainment of both national standards and the WHO IT-1 more feasible, while generating shared benefits across the airshed.

5. Discussion

Our analysis identifies five sectors as indispensable for achieving substantial air quality improvements in UP over the coming decade: (i) residential/commercial biomass burning, (ii) agriculture sector, (iii) transportation and road dust, (iv) medium and small industries, and (v) municipal waste burning (to a lesser extent). From a technical perspective, interventions in these sectors represent low-hanging fruits for reducing population-weighted $PM_{2.5}$ exposure. Other sectors can and should contribute, yet their impact is secondary; progress in these areas cannot compensate for the absence of effective action in the dominant sectors. While current policies have begun to address some sources - such as technology upgrades in brick kilns and emission controls in power generation - significant untapped potential remains, particularly in agriculture (e.g. fertilizers use) and the residential sector. Importantly, the relevance of these sectors becomes even more pronounced when the entire airshed, including rural areas and processes driving secondary particle formation, is considered. This broader systems perspective highlights those comprehensive strategies, extending beyond urban centers and individual sources, are essential to achieving meaningful and sustained reductions in $PM_{2.5}$ exposure.

The limited availability of comprehensive statistical data introduces unavoidable uncertainties and potential biases in the emission reduction estimates. The emissions inventory underpinning the GAINS-IGP model for UP underwent an extensive review in 2023; nevertheless, important gaps remain. For example, while official statistics were used for municipal solid waste management, excluding the informal waste sector leads to significant underestimation. Accounting for informal waste handling could increase sectoral emissions by a factor four or five, with an associated exposure reduction potential of up to 8 $\mu g/m^3$. In agriculture, controls are limited, yet the counterfactual FLE scenario projects higher livestock numbers and fertilizer use. Consequently, $PM_{2.5}$ concentrations in the baseline scenario are reduced by approximately 0.5 $\mu g/m^3$. Similarly, data on manure management practices in large industrial cattle farms are sparse, and forward-looking projections to 2035 are not robust.

The current assumption that all farms rely on solid manure systems may underestimate emissions, as new industrial holdings are more likely to employ liquid systems, which generate significantly higher ammonia emissions during storage and application. Importantly, a range of cost-effective mitigation options exist for this sector, but their prioritization depends on accurate baseline data. These examples underscore the importance of continued refinement of the emissions inventory, particularly for waste management and agricultural practices. Improving the resolution and reliability of activity data in these sectors would not only reduce uncertainties in modeled outcomes but also sharpen the basis for policy prioritization and cost-effective intervention design. Future data-collection priorities should focus on improving activity data for waste handling, agricultural practices, and livestock management to reduce uncertainties in modeled outcomes and support cost-effective policy interventions. Future efforts should expand monitoring in rural and peri-urban areas, including $PM_{2.5}$ and PM_{10} measurements as well as indoor air quality in households using solid fuels, complemented by satellite observations and low-cost sensors.

Key additional sectoral measures - and their associated costs - for addressing air pollution in Uttar Pradesh have been identified. Yet translating technical potential into effective emission reductions requires carefully designed and financed interventions, supported by institutional capacity and enforcement. Recent experiences with comparable policy initiatives in India illustrate the practical challenges of implementation, including distributional impacts, social acceptability, governance constraints, finance gaps, and enforcement limitations. In sectors where measures are already in place, systematic evaluation of current schemes and complementary interventions is critical.

For example, the *Ujjwala* scheme was launched to accelerate the transition from biomass to LPG-based cooking among low-income households (GoI, 2019a). However, the affordability of refills remains a key barrier (Gill-Wiehl et al., 2022; Kar et al., 2020; Mani et al., 2020). Gill-Wiehl et al. (2022) estimate that despite initial distribution of free connections, only 30–40% of households maintain regular LPG refills due to cost constraints, indicating that actual adoption falls well below target levels. This limited uptake reduces the expected air quality and health co-benefits in practice, highlighting the need for complementary financing mechanisms, such as targeted subsidies or pay-as-you-go schemes. Adoption is further constrained by awareness and accessibility issues in rural areas, where supply chains may be less developed. Enforcement challenges are also critical in rural residue burning. Despite bans on crop residue burning, field observations and satellite-based assessments indicate that over 60% of rice residue in rural UP is still burned in situ (Gill-Wiehl et al., 2022). Weak enforcement capacity, combined with low availability of mechanized alternatives and the high labor costs of manual residue removal, limits the effectiveness of existing regulations. Quantitative estimates suggest that reducing rural residue burning by 50% could lower annual $PM_{2.5}$ concentrations by 2–3 μg/m^3 in nearby urban centers, underscoring the magnitude of this barrier.

Similar challenges persist in waste management and dust control, despite substantial financial commitments through programs such as XV-FC (GoI, 2019b), NCAP, and related convergence initiatives (Ganguly et al., 2020; GoI, 2019a; Manojkumar and Muruganandam, 2025). Non-attainment cities in UP have already drawn on approximately €250 million from NCAP and XV-FC for city-level action plans. Nevertheless, persistent knowledge gaps, limited technical and institutional capacity, and weak coordination threaten to reduce the effectiveness of these investments. Addressing these shortcomings will require prioritizing data collection to fill rural and peri-urban monitoring voids, enhancing statistical systems, and strengthening technical and enforcement capacity. Tailored approaches, including shared knowledge platforms, reliable air quality monitoring networks, and mechanisms to close implementation gaps, will be critical for translating investments into tangible air quality improvements.

India's current city-centered approach to air quality management has delivered only incremental improvements, leaving national trends largely unchanged (Guttikunda et al., 2025; Xie et al., 2024). Achieving the NAAQS and WHO IT-1 targets in UP will require acknowledging that roughly one-third of the state's $PM_{2.5}$ exposure originates from sources outside its borders, within the wider IGP airshed. For many urban areas, this external contribution dominates local $PM_{2.5}$ concentrations. This underscores the need for regional cooperation, alongside raising awareness and strengthening enforcement at the local level. To deliver durable progress, clean air strategies must adopt a holistic, staged transition pathway. Such pathways should incorporate pilot interventions, clear timelines, and definite end-dates for intermediate steps, ensuring consistency with other policy priorities and maximizing co-benefits – particularly for greenhouse gas mitigation – while avoiding unintended trade-offs.

While this study provides a comprehensive assessment of air quality and mitigation strategies in UP, certain limitations should be acknowledged. The atmospheric simulations are based on meteorological conditions from a single representative year (2018). Although the EMEP simulations capture interannual variability that may influence $PM_{2.5}$ formation and dispersion, our analysis relies on annual averages, which may smooth out short-term fluctuations. Transboundary pollution inflows were held constant to isolate the impacts of local emission sources; however, future changes in emissions across the IGP could alter cross-border transport patterns. The policy scenarios assume full implementation and effectiveness of emission control measures, whereas actual outcomes may vary depending on enforcement, technological adoption, and compliance rates. Finally, emission projections and cost estimates are contingent on assumptions regarding economic development, energy demand, and mitigation costs within the GAINS framework, introducing some uncertainty into long-term projections. Despite these limitations, the study provides a robust basis for identifying key sectors and interventions for improving air quality and informing realistic policy pathways.

6. Conclusions

This study, using the GAINS framework, identifies the residential, commercial, agricultural, transportation, industrial, and municipal waste sectors as the dominant contributors to $PM_{2.5}$ exposure in Uttar Pradesh (UP). The analysis suggests that existing air quality policies and regulations will likely stabilize ambient $PM_{2.5}$ concentrations over the next decade at 67.5 μg/m^3, even amid population growth and a projected 2.5-fold increase in GDP. Full implementation of current measures is expected to hold levels near the 2020 baseline of 65.4 μg/m^3, a stabilization, but still far above both national standards (40 μg/m^3) and international health benchmarks. The residential sector, dominated by continued reliance on solid fuels for cooking, is projected to remain the single largest contributor, accounting for roughly one-third of the total exposure in 2035. Other major sources include transportation, small-scale industries (e.g., brick kilns), fertilizer use, and municipal waste burning. In contrast, in the absence of stringent policy enforcement, economic expansion is expected to cause a marked deterioration in air quality. Under the FLE scenario, population-weighted exposure is projected to increase by 47% relative to 2020, reaching 96 μg/m^3 by 2035. These findings underscore the critical importance of rigorous implementation of existing policies to prevent further escalation of health risks associated with $PM_{2.5}$ pollution.

Despite this, policy attention has historically centered on on-road vehicles and large power plants, potentially overlooking the disproportionate role of household emissions and decentralized sources. The findings highlight the need for a holistic mitigation strategy that integrates all major pollution sources, prioritizes cost-effective interventions, and explicitly addresses the residential sector. Effective air quality management will depend on clear attribution of sources, rigorous evaluation of the health and economic benefits of action, and careful consideration of socio-economic trade-offs. Without such a comprehensive approach, UP risks continued stagnation at unsafe pollution levels; with it, substantial and sustainable improvements in public health and environmental quality are within reach.

This assessment also evaluates the potential of globally validated measures to further improve air quality by 2035. In UP, their adoption could reduce $PM_{2.5}$ exposure by an additional ~30 μg/m^3 beyond the Current Legislation (CLE) pathway. Five sectors emerge as particularly pivotal: (i) residential and commercial biomass burning, (ii) agriculture, (iii) transport and dust, (iv) small and medium-scale industries, and (v) municipal waste burning. These areas offer technically feasible and cost-effective opportunities, and while progress in other sectors would be valuable, it cannot compensate for inaction in these dominant contributors. Even under full deployment of available measures within UP, exposure would only decline to ~41 μg/m^3 by 2035, remaining above the WHO Interim Target 1 (35 μg/m^3). This shortfall reflects the substantial influence of external sources - notably transboundary inflows from neighboring states and natural background dust, which are projected to contribute about 30 μg/m^3.

Achieving sustained compliance will therefore require a cooperative airshed approach. Coordinated actions across all IGP states, built around a shared set of core interventions, could reduce average $PM_{2.5}$ exposure in UP to below 35 μg/m^3. Such regional coordination would not only improve air quality across the airshed but also ease UP's reliance on its most costly control options, thereby reducing overall mitigation expenditures and maximizing collective benefit.

CRediT authorship contribution statement

Pallav Purohit: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Wolfgang Schöpp:** Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Parul Srivastava:** Writing – review & editing, Visualization, Validation, Software, Data curation. **Fabian Wagner:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis. **Zbigniew Klimont:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition. **Gregor Kiesewetter:** Writing –

review & editing, Visualization, Validation, Software, Methodology. **Sagnik Dey:** Writing – review & editing, Supervision, Funding acquisition. **Jostein Nygard:** Writing – review & editing, Project administration, Conceptualization. **Ashish Tiwari:** Writing – review & editing, Project administration. **Mukesh Sharma:** Writing – review & editing, Validation. **Markus Amann:** Writing – review & editing, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Conceptualization. **Adriana Gomez-Sanabria:** Data curation. **Susanna Dedring:** Writing – review & editing. **Pallavi Joshi:** Data curation. **Himanshu Lal:** Data curation. **Sanjukta Ghosh:** Data curation. **Robert Sander:** Software. **Binh Nguyen:** Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors would like to thank the three anonymous reviewers for their helpful and constructive comments that greatly contributed to improving the final version of the paper. The modeling work conducted by IIASA was funded by the World Bank (Grant No. 7197729), while IIT Delhi's work was supported by the World Bank (Grant No. 7198197) under its Regional Air Quality Management Program in the Indo-Gangetic Plain (IGP) region. We gratefully acknowledge the support provided by the Department of Environment, Forest and Climate Change, Government of Uttar Pradesh (DoEFCC, GoUP) for conducting this study. We are also grateful to Mr. Maneesh Mittal, Mr. Pranav Jain, and Mr. Mohd. Rahib from DoEFCC, GoUP; Ms. Karin Shepardson, Ms. Farah Zahir, Ms. Ishaa Srivastava, Mr. Sayantan Sarkar, and Ms. Neha Sharma from the World Bank; Late Dr. Bipasha Ghosh from IIT Delhi, and Dr. Anju Goel and Mr. Nimish Singh from The Energy and Resources Institute (TERI) for their valuable insights during the course of this study. Sagnik Dey acknowledges support through the Fellowship of the Vipula and Mahesh Chaturvedi Chair in Policy Studies at IIT Delhi. The manuscript was prepared entirely by the human authors, with ChatGPT used only to improve readability and correct typographical errors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.129784.

Data availability

Data will be made available on request.

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