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Climate Co-Benefits of Black Carbon Mitigation

in the Indo-Gangetic Plain

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Executive Summary

Climate change and poor air quality are among the most pressing environmental challenges today. In addition to long-lived greenhouse gases, certain short-lived climate pollutants can accelerate global warming while also degrading air quality. Black carbon is one such pollutant. It contributes to atmospheric heating by absorbing visible light and is also a component of $PM_{2.5}$, which is associated with severe health risks and life-threatening diseases.

This study evaluates black carbon emission-reduction scenarios that can deliver climate co-benefits alongside improvements in air quality and public health across the Indo-Gangetic Plain (IGP). Air quality benefits and corresponding health benefits are estimated using a reduced complexity air quality model called REACH (Rapid Estimation of Air Concentration for Health). The health benefits are estimated based on reductions in total $PM_{2.5}$ concentrations under the defined emission scenarios, which may result in an underestimation of the actual health benefits. Climate co-benefits are assessed using CO_2-equivalent metrics and changes in radiative forcing across different emission-reduction scenarios.

Two CO_2-equivalent metrics are considered in this report. Global Warming Potential (GWP) measures the cumulative energy absorbed by a pollutant or greenhouse gas relative to CO_2 over a specified time period. Global Temperature Potential (GTP) measures the global mean temperature change caused by a pollutant or greenhouse gas relative to CO_2 over a specific point in time.

The study also estimates the amount of additional energy prevented from entering the Earth's atmosphere over one year as a result of reduced black carbon emissions.

Key Insights

- **There are significant air quality and climate co-benefits from domestic emissions reduction across the IGP.**

  The domestic sector is the major source of black carbon across all IGP states, with Uttar Pradesh accounting for the largest share. A 60% reduction in black carbon emissions from the domestic sector in Uttar Pradesh alone could reduce black carbon concentrations by 12.6% and avoid 836 $PM_{2.5}$-attributable premature deaths across the IGP. The climate co-benefits for this scenario are estimated at 170 million tonnes (Mt) CO_2-equivalent using GWP10 and 94 Mt CO_2-equivalent using GTP10.

- **IGP-wide domestic-sector action delivers larger benefits than state-specific action.**

  When the IGP is treated as a single airshed, the benefits are substantially greater. A 50% reduction in domestic-sector black carbon emissions across all IGP states results in a 23.7% decrease in black carbon concentrations and avoids 1,455 $PM_{2.5}$-attributable premature deaths. This airshed-level domestic-sector scenario delivers more than twice the CO_2-equivalent benefits of the 60% reduction in Uttar Pradesh alone.

- **A multisectoral airshed approach delivers the largest combined air quality, health, and climate benefits.**

  The largest benefits are achieved through a multisectoral airshed approach. Reducing black carbon emissions from all major sources in the IGP results in a 37% reduction in black carbon concentration and prevents 2,290 $PM_{2.5}$-attributable premature deaths. This scenario also provides climate co-benefits estimated at 639.3 Mt CO_2 equivalent using GWP10 and 352.2 Mt CO_2 equivalent using GTP10.

- **Climate benefits are strong in the near term, reinforcing the value of black carbon mitigation.**

  The multisectoral airshed scenario reduces atmospheric energy absorption by approximately 6 terawatts (TW) over one year because of lower black carbon levels, indicating immediate climate benefits.

Overall, the analysis shows that mitigating black carbon can deliver significant climate and health benefits. It also demonstrates that an airshed-based, multisectoral approach with coordinated action across multiple states can provide considerable benefits across the region by facilitating substantial reductions in black carbon levels.

Policy Implications

- **Black carbon monitoring needs to be strengthened.**

  Similar to the existing Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network, which monitors $PM_{2.5}$ and other pollutants, black carbon should be monitored at representative locations nationwide. This would help track black carbon concentrations and assess the effectiveness of mitigation strategies.

- **Black carbon should be identified explicitly as a policy target.**

  At present, it is rarely treated as a distinct pollutant within existing air quality and climate policy frameworks. Including black carbon in programmes such as the National Clean Air Programme (NCAP), the State Action Plan for Climate Change (SAPCC), and city clean air action plans can strengthen mitigation efforts.

- **Policy action should prioritise sectors with high black carbon emissions.**

  Sectors such as households, diesel-powered heavy transport, and industrial combustion should be prioritised, as they emit soot and contribute to black carbon levels. Reducing emissions from these sectors can slow the rate of global temperature rise and help avoid irreversible climate tipping points.

- **Air quality and climate policy need to be better aligned.**

  Recognising air quality improvement as a critical component of near-term climate mitigation is particularly important in highly polluted regions such as the IGP. Stronger alignment between India's Nationally Determined Contributions and NCAP can support coordinated action across states and sectors.

A coordinated approach that links sectoral interventions with regional airshed governance can accelerate progress towards cleaner air while contributing to India's near-term climate mitigation goals.

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List of Abbreviations

Abbreviation	Definition
AQI	Air Quality Index
BS	Bharat Stage
CAAQMS	Continuous Ambient Air Quality Monitoring Stations
CAQM	Commission for Air Quality Management in National Capital Region and Adjoining Areas
CCAC	Climate and Clean Air Coalition
CEDS	Community Emission Data System
CNG	Compressed Natural Gas
COPD	Chronic Obstructive Pulmonary Disease
CPCB	Central Pollution Control Board
CVD	Cardiovascular disease
CO	Carbon monoxide
CO_2	Carbon dioxide
EDGAR	Emissions Database for Global Atmospheric Research
EDGAR-HTAP	Emissions Database for Global Atmospheric Research – Hemispheric Transport of Air Pollution
FAME	Faster Adoption & Manufacturing of Electric vehicles
FCBTK	Fixed Chimney Bull's Trench Kiln
FGD	Flue Gas Desulphurization
GBD	Global Burden of Disease
GDP	Gross Domestic Product
GFED	Global Fire Emissions Database
GHG	Greenhouse gases
GRAP	Graded Response Action Plan
GWP	Global Warming Potential
GTP	Global Temperature Potential
HFC	Hydrofluorocarbon
IGP	Indo-Gangetic Plain
IHD	Ischemic Heart Disease
LPG	Liquified Petroleum Gas
LRI	Lower Respiratory Infection
MoEFCC	Ministry of Environment, Forest and Climate Change
MoHI	Ministry of Heavy Industries
MoP	Ministry of Power
MoPNG	Ministry of Petroleum and Natural Gas

Abbreviation	Definition
MoRTH	Ministry of Roads, Transport and Highways
MR-BRT	Meta Regression Bayesian Regularized, Trimmed
MT	Million tonnes
NAAQS	National Ambient Air Quality Standards
NAAQM	National Ambient Air Quality Monitoring
NAMP	National Air Quality Monitoring Programme
NCAP	National Clean Air Programme
NCR	National Capital Region
NCT	National Capital Territory
NDC	Nationally Determined Contribution
PAF	Population Attributable Fraction
$PM_{2.5}$	Particulate matter with diameter less than 2.5μm
PM_{10}	Particulate matter with diameter less than 10μm
PMUY	Pradhan Mantri Ujjwala Yojana
PNG	Piped Natural Gas
PPCB	Punjab Pollution Control Board
PWM	Population Weighted Mean
REACH	Rapid Estimation of Air Concentration for Health
RR	Relative Risk
SAPCC	State Action Plan for Climate Change
SDG	Sustainable Development Goals
SLCP	Short-lived Climate Pollutant
SFP	Specific Forcing Pulse
SOA	Secondary Organic Aerosols
SPCB	State Pollution Control Board
TW	Terawatt
ULB	Urban Local Body
UNFCCC	United Nations Framework Convention on Climate Change
UP CAMP	Uttar Pradesh Clean Air Management Programme
WHO	World Health Organisation

1. Introduction

Black carbon, also known as soot, is a component of fine particulate matter ($PM_{2.5}$), accounting for approximately 5%–25% of ambient $PM_{2.5}$ concentrations (Clean Air Fund, 2025). It forms during the incomplete combustion of fossil fuels and biomass, including in industrial processes, diesel engines, open waste burning, crop-residue burning, forest fires, and cooking and heating with biofuels (Ramanathan & Carmichael, 2008).

Although black carbon remains in the atmosphere for approximately one week, its light-absorbing properties influence the Earth's radiation budget by absorbing solar radiation and accelerating atmospheric warming through the direct radiative effect (Ramanathan & Carmichael, 2008). It is considered the second-most important climate-forcing agent after carbon dioxide (CO_2) (Bond et al., 2013) and can affect the hydrological cycle (Douville et al., 2021). At the regional level, studies suggest that black carbon can adversely affect the Indian summer monsoon (Debnath et al., 2024). Its deposition on snow also reduces surface albedo, increases solar radiation absorption, and accelerates snowmelt (Kang et al., 2020).

Black carbon mitigation is important not only for climate reasons but also for public health. Studies have highlighted associations between black carbon exposure and cardiovascular disease (CVD) mortality (Li et al., 2016; Cao et al., 2012); oxidative stress indicators at the cellular level (Guascito et al., 2023); hypertension (Singh et al., 2025); and premature mortality (Yang et al., 2021). Its increased capacity to generate reactive oxygen species makes black carbon more hazardous than several other inorganic components of fine particulate matter (Daellenbach et al., 2020). Furthermore, the health risk of CVD is estimated to be 6 to 26 times greater for black carbon than for undifferentiated particulate matter (Li et al., 2016; Ostro et al., 2004; Laden et al., 2006).

Therefore, reducing black carbon emissions could help lower $PM_{2.5}$ concentrations, particularly in regions where combustion sources dominate. These reductions can improve air quality while also advancing multiple Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being), SDG 7 (Affordable and Clean Energy), and SDG 11 (Sustainable Cities and Communities). Planning and implementing strategies to reduce emissions of this super pollutant can help mitigate near-term warming, avoid irreversible climate tipping points, enhance societal resilience, and improve air quality.

This study focuses on identifying sources of black carbon emissions in the Indo-Gangetic Plain (IGP), one of the most densely populated regions in the world and a major hotspot of $PM_{2.5}$ pollution. Since black carbon is a component of $PM_{2.5}$, strategies aimed at reducing $PM_{2.5}$ concentrations are also likely to reduce black carbon levels in the region. During the post-monsoon and winter seasons, unfavourable meteorological conditions limit pollutant dispersion, leading to pollutant accumulation and exposure to dangerously high levels of black carbon and $PM_{2.5}$. Furthermore, the IGP's proximity to the Himalayas increases the region's climatic sensitivity, making black carbon mitigation an urgent priority. This study assesses the impacts of these emissions reduction on air quality and uses multiple climate metrics, such as Global Warming Potential (GWP) and Global Temperature Potential (GTP), to evaluate the co-benefits of reducing black carbon compared with CO_2.

The report evaluates the impacts of black carbon emission-reduction scenarios on air quality and the associated health and climate co-benefits. Climate co-benefits are quantified in terms of CO_2-equivalent impacts and reductions in radiative forcing due to decreased black carbon absorption. Air quality benefits are estimated using the Rapid Estimation of Air Concentration for Health (REACH), an annually averaged reduced-complexity air quality model. REACH-derived pollutant concentrations, combined with Meta Regression Bayesian Regularised, Trimmed (MR-BRT) splines as a function of $PM_{2.5}$ exposure, are used to estimate associated health impacts. Since black carbon concentrations are not measured by the Continuous Ambient Air Quality Monitoring Stations (CAAQMS) network, the model is validated against total $PM_{2.5}$ concentration. Black carbon is a component of $PM_{2.5}$, and combustion sources largely influence the patterns of both pollutants; hence, $PM_{2.5}$ is used as a proxy for black carbon in model evaluation. Overall, this quantitative framework integrates emission scenarios and air quality modelling to evaluate the associated benefits, underscoring the importance of prioritising mitigation of short-lived climate pollutants (SLCPs) in the IGP.

2. Methodology

2.1. Air quality modelling framework

REACH, a reduced-complexity model, is used to compute concentrations of $PM_{2.5}$ and black carbon. The model domain covers the Indian subcontinent, including all states within the IGP. Annual average pollutant concentrations are computed at a spatial resolution of 25 km by multiplying grid-wise source–receptor relations (µg/m^3 per tonne of emissions) with gridded emissions for five different $PM_{2.5}$ constituents. These source–receptor relations represent the change in pollutant concentration at each receptor grid cell resulting from one tonne of emissions released from a given source grid cell. Pollutant dispersion at each grid cell is represented using a non-steady-state Gaussian plume approach, while chemical transformations and deposition processes are represented using first-order loss terms.

Input emissions to the REACH model include primary $PM_{2.5}$ (including black carbon, organic carbon, and mineral matter); sulphur dioxide (a precursor to sulphate aerosols); nitrogen oxides (precursors to nitrate aerosols); ammonia (a precursor to ammonium nitrate and ammonium sulphate); and volatile organic compounds (precursors to secondary organic aerosols). Additional details of the REACH model setup used in this study are provided in Annexure 1. More details can be found in Akindele et al. (2024).

2.2. Health and climate co-benefit calculations

2.2.1. Health benefits

Health benefits are presented as avoidable $PM_{2.5}$-attributable mortality in response to air quality benefits corresponding to emission-reduction scenarios. For a defined emission-reduction scenario, reductions in $PM_{2.5}$ concentrations are calculated, and the associated mortality burdens are estimated for two age groups, following McDuffie et al. (2021):

- **Age >25 years**: chronic obstructive pulmonary disease (COPD), lung cancer, ischemic heart disease, stroke, type 2 diabetes, and lower respiratory infections (LRIs)

- **Age <5 years:** LRIs.

The population attributable fraction (PAF) for each disease is estimated state-wise using the population-weighted mean (PWM) $PM_{2.5}$ concentration and the corresponding relative risk (RR) functions derived from MR-BRT splines. These relative risk functions are based on population-weighted $PM_{2.5}$ exposure and are gender-independent, representing the excess risk of non-accidental mortality associated with each disease. $PM_{2.5}$-attributable premature deaths for each disease and age group are estimated by multiplying the PAF by the corresponding baseline mortality rates derived from the Global Burden of Disease.

2.2.2. Climate co-benefits

The climate benefits are quantified using CO_2 equivalent metrics and changes in radiative forcing.

- CO_2 equivalent benefits represent the climatic impact of reduced black carbon emissions by expressing them as the equivalent effect of mitigating an amount of CO_2. These benefits are calculated using two commonly applied metrics:

» **Global Warming Potential (GWP)**: GWP measures how much energy the emission of 1 tonne of a gas or pollutant will absorb over a given period, relative to the emission of 1 tonne of CO_2. GWP represents time-integrated radiative forcing.

» **Global Temperature Potential (GTP):** GTP quantifies the change in global mean surface temperature at a chosen point in time in response to an emission pulse, relative to CO_2. GTP is an endpoint temperature-based metric for the study period.

- Because black carbon has a much shorter atmospheric lifetime than CO_2, the choice of time horizon strongly affects the estimated climate benefits. In this study, 10-year and 20-year time horizons are used to calculate the CO_2-equivalent benefits of reducing black carbon emissions. The GWP and GTP metrics are derived from Myhre et al.'s (2014) study.

- Changes in radiative forcing for each emission-reduction scenario are estimated using Specific Forcing Pulse (SFP), as reported by Bond et al (2011). SFP is defined as the total energy added to the Earth–atmosphere system by one gram of pollutant emitted in a region during its entire lifetime. SFP is particularly suitable for SLCPs such as black carbon because it captures short-term radiative effects. The additional energy absorbed alters the Earth's radiative balance until a new thermal equilibrium is achieved (Lam et al., 2012).

For all metrics, the climate benefit of an emission-reduction scenario is calculated as follows:

Climate benefit = Climate metric x (Baseline emissions – Scenario emissions).

In the equation above, when estimating CO_2-equivalent climate benefits, the climate metric is GWP or GTP. For radiative-forcing calculations in this study, the climate metric used is SFP.

2.3. Black carbon emission sources in the IGP

To provide context for the emission inventory and the emission-reduction scenarios, this section summarises the major sources of black carbon emissions in the IGP. Black carbon is emitted due to the incomplete combustion of carbon-rich fuels such as fossil fuels, biomass (e.g. wood and crop residues), and biofuels (e.g. dung cakes and biogas). These fuels are typically used in residential cooking and heating, transport, heavy industries, small-scale informal industries such as brick manufacturing, and agricultural activities. The following subsections describe the key sectors that contribute to black carbon emissions in the IGP.

2.3.1. Residential cooking and heating

One of the significant sources of black carbon emissions in the IGP is the widespread use of solid fuels such as wood, charcoal, dung cakes, and agricultural residue. Solid fuel use for cooking is a consistent source of black carbon emissions in rural areas and among low-income households in urban and peri-urban areas of the IGP. These emissions depend on cooking duration, the number of meals prepared, fuel type, stove technology and efficiency, cooking practices such as ignition process and timing, and kitchen ventilation efficiency (Chakraborty et al., 2025). During winter, solid fuels are also used for space heating, thereby increasing black carbon emissions.

2.3.2. Brick kilns

Brick kilns are a source of black carbon emissions in the IGP (Tibrewal et al., 2023). About 45% of the country's brick production is concentrated in the IGP, primarily in rural and peri-urban areas. Traditional fixed chimney bull's trench kilns (FCBTKs) dominate brick production in the IGP and are among the most polluting and primitive technologies. These kilns emit higher levels of black carbon than other technologies (Haque et al., 2018). FCBTK emits roughly 69% more black carbon emissions than zig-zag kilns, which are a relatively cleaner alternative (Greentech Knowledge Solutions Pvt Ltd et al., 2012). Along with the kiln type, the fuel type can also intensify the black carbon emissions. Coal combustion in brick kilns is a major source of black carbon emissions. More than 50% of the country's coal-dominated kilns are found in northern India, the IGP, and eastern India, with a few biomass-dominated kilns also found in the IGP (Tibrewal et al., 2023).

2.3.3. Transport

The transport sector is one of the main contributors to black carbon emissions in the IGP and across India. Black carbon is emitted from the incomplete combustion of fossil fuels, especially diesel, in internal combustion engines. Heavy-duty vehicles; off-road vehicles (e.g. farm vehicles); and machinery (e.g. road paving equipment, construction equipment, cranes, locomotives, ferries, and harbour boats) are significant contributors to black carbon emissions (Clean Air Fund, 2025).

Heavy-duty vehicles account for less than 2% of the vehicle fleet; however, they contribute approximately 70% of total tailpipe $PM_{2.5}$ emissions in India. Black carbon emissions from these vehicles in the baseline year 2022 are estimated at 100–129 kilotonnes (kt) per year in India (CSTEP, 2025). The relative contribution is even higher from older and poorly maintained vehicles, which are referred to as 'super-emitters'. Super-emitters account for 62% of $PM_{2.5}$ emissions from India's heavy commercial vehicle fleet. This vehicle segment is, therefore, a significant source of black carbon emissions due in part to the higher prevalence of diesel-powered vehicles.

Vehicle electrification can significantly reduce black carbon emissions. However, efforts have largely focused on passenger vehicles and two- or three-wheeler segments. The freight sector has remained largely untouched by electrification, apart from a few small-scale pilot initiatives. This is likely due to factors such as the sector's highly fragmented nature, with many small-scale truck owners; limited maturity and economic viability; near-zero social uptake; and a lack of targeted financial incentives. For instance, the PM Electric Drive Revolution in Innovative Vehicle Enhancement (PM E-DRIVE) scheme has only about INR 500 crores allocated for e-trucks. Furthermore, the modal share of railways in freight transport has decreased from 39% to 26%, while the number of diesel trucks has increased.

2.3.4. Agricultural waste burning

Agriculture remains an important contributor to India's economy and provides livelihoods for a large share of the population (Office of the Registrar General & Census Commissioner, 2011). Rice and wheat are two of the most cultivated crops, and the post-harvest residues are often burnt. Farmers often choose burning as a quick method to clear fields because of the short window between two consecutive crops and the use of mechanical harvesters, which leave about 20–30 cm of stubble in the ground, making field preparation for the next crop difficult (Dutta et al., 2022).

This practice is highly prevalent in states such as Punjab and Haryana in the IGP, although farm fire incidents have been recorded across the country. A study conducted in Punjab showed that black carbon concentration in Patiala was much higher, at approximately 25 μg/m^3, than in other Indian cities during October–November 2008, indicating the episodic impact of agricultural waste burning (Kharol et al., 2012).

2.4. Emission inventory

The key objective of this study is to quantify the regional-scale impacts of black carbon reduction and assess the associated long-term health and climate co-benefits. Such an analysis requires a regional-level emissions inventory; however, India currently lacks a comprehensive national- or IGP-level inventory. To address this gap, a hybrid emissions inventory was developed by integrating multiple global emissions inventories and model outputs to estimate sub-sectoral emissions of major pollutants across the study region. The same emissions inventory was also used in *Beyond State Boundaries: Quantifying Interstate Air Pollution Transport and Sectoral Solutions in the Indo-Gangetic Plain* (CSTEP, 2026), a chemical transport modelling study of the region.

Emissions from major anthropogenic sources are derived from the Community Emission Data System (CEDS) inventory (McDuffie et al., 2020). CEDS categorises anthropogenic emissions into eight major sectors: agriculture, energy, industry, transportation, residential/domestic, solvent production and application, waste, and international shipping. The inventory has a spatial resolution of 0.1°, approximately 10 km. Agricultural waste, or crop residue, burning emissions are obtained from the Global Fire Emissions Database (GFED) version 4.1 (Randerson et al., 2017), which has a spatial resolution of 0.25°, approximately 25 km. Both CEDS and GFED emissions are re-gridded to the REACH model grid at 25 km resolution for consistency in the subsequent analysis.

Figure 1: *Percentage share of major black carbon-emitting sources contributing to annual total black carbon (A) and $PM_{2.5}$ emissions (B) over the IGP. The annual totals (in kilotonnes) are indicated at the centre of the pie chart.*

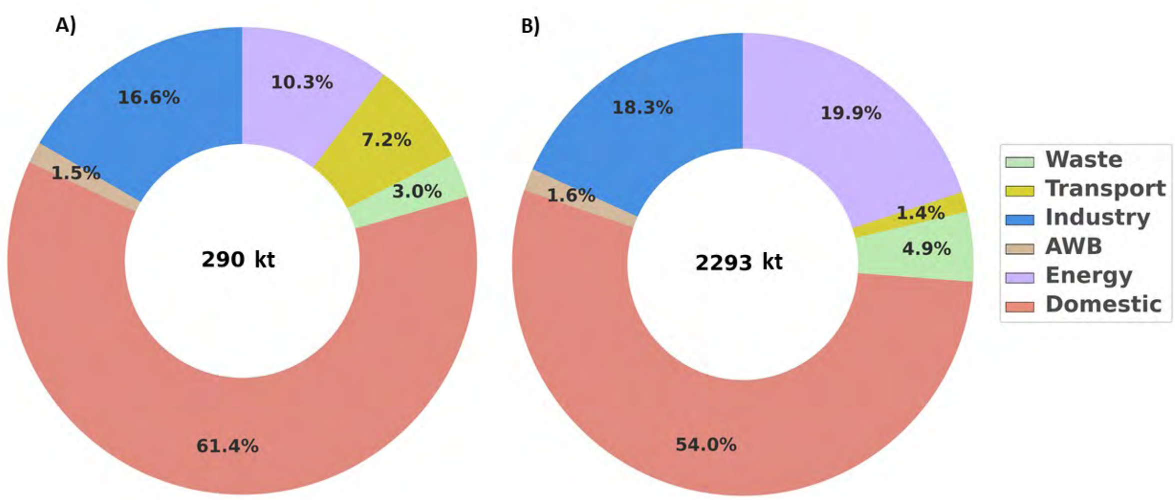
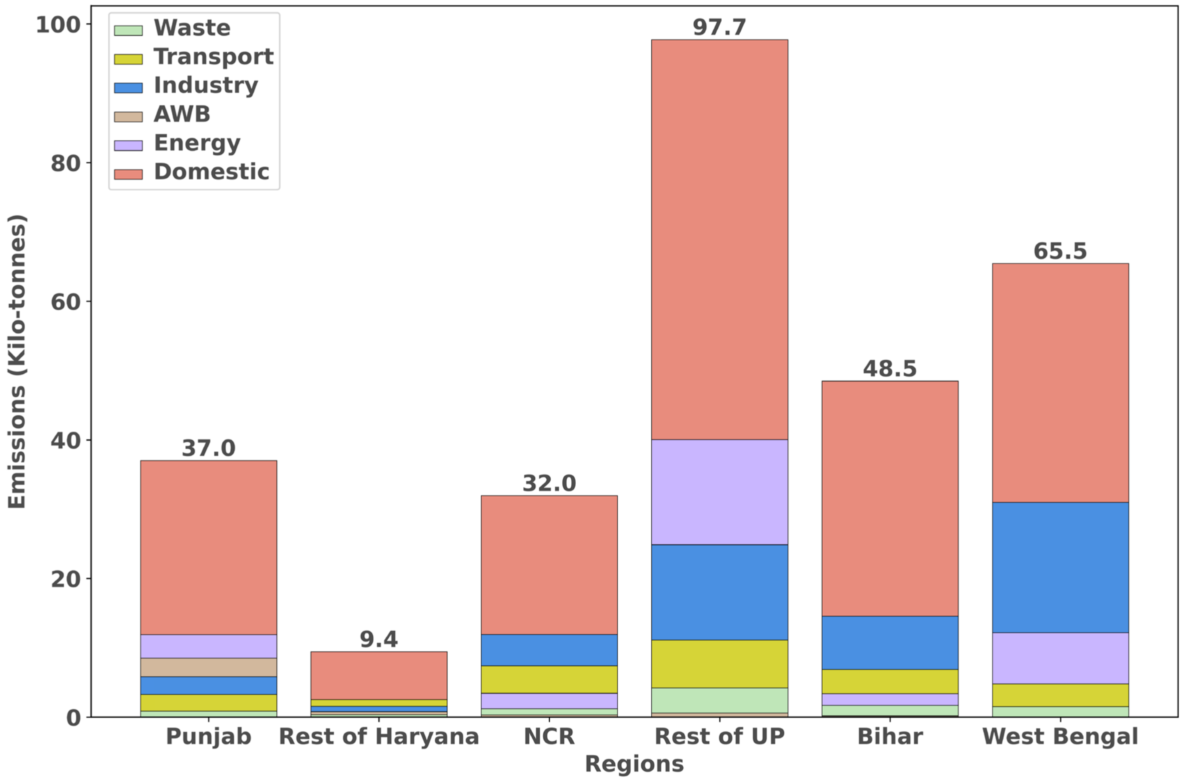


Figure 1 shows the percentage share of annual black carbon and $PM_{2.5}$ emissions from major anthropogenic sources in the IGP. Total annual black carbon emissions in the IGP are estimated at 290 kt, accounting for approximately 32% of India's total black carbon emissions. The largest contributors in the IGP are domestic cooking and heating, which account for 61.4% of black carbon emissions and 54% of $PM_{2.5}$ emissions. The next two major contributors are industry and energy. About 16.6% of black carbon emissions originate from industrial processes, while energy generation contributes approximately 10%. For $PM_{2.5}$, the relative contributions from these sectors are comparatively higher. These results indicate that black carbon and $PM_{2.5}$ largely share common emission sources across the region. Other sources of black carbon include transport, which accounts for 21 kt of annual emissions, and open waste burning, which accounts for 8.7 kt of annual black carbon emissions in the IGP. Since agricultural waste burning peaks only during April–May and October–November, its annual contribution to black carbon emissions is less than 2%.

Figure 2: Stacked bar plots showing the sectoral contribution to black carbon emissions in the IGP region.



Note: AWB: Agricultural waste burning; NCR: National Capital Region; UP: Uttar Pradesh.

The contributions of different emission sources by state and region in the IGP are presented in Figure 2. The domestic sector emerges as the dominant source of black carbon over the IGP, followed by industrial processes and energy generation. In place of Delhi, the National Capital Region (NCR) is considered along with other states in the IGP. Since multiple districts in Haryana and Uttar Pradesh are part of the NCR, the remaining districts in these states are shown as 'Rest of UP' and 'Rest of Haryana'.

Punjab, located in the upper IGP, emits 37 kt of black carbon. In 2019, the top three contributors in the state were the domestic sector (25 kt), the energy sector (3.4 kt), and agricultural waste burning (2.7 kt). The Rest of Haryana contributes 3.3% of the IGP's black carbon emissions. Here too, the domestic sector dominates, followed by the transport sector, which emits 1 kt of black carbon and is the second-largest source in the region. The domestic sector is also the largest black carbon emitter in NCR (20 kt), followed by transport and industry, which contribute approximately 4 kt.

The Rest of UP is the largest black carbon emitter in the IGP, accounting for 97.7 kt of regional black carbon emissions, with domestic emissions contributing the highest share at 59%. Bihar accounts for 16.7% of the IGP's total black carbon emissions, with the major sources being the domestic sector (34 kt), industrial emissions (7.7 kt), and transport (3.5 kt). West Bengal is the second-largest contributor to the IGP's total black carbon emissions, accounting for 22.6%. In West Bengal, the domestic sector contributes 34.5 kt, followed by industrial emissions (18.8 kt) and the energy sector (7.4 kt).

Overall, cumulative black carbon emissions in the IGP are approximately 290 kt, accounting for a large fraction (32%) of India's total black carbon emissions. The Rest of UP and West Bengal are the two highest-emitting regions, while the rest of Haryana is the least-emitting region. Bihar, Punjab, and the NCR account for 16.7%, 12.8%, and 11% of the IGP's black carbon emissions, respectively.

2.5. Emission-reduction scenarios

For this study, 10 emission-reduction scenarios were designed to assess effective combinations of control measures to reduce black carbon concentrations, thereby also reducing $PM_{2.5}$ concentrations in the IGP. These scenarios include state-centric, region-centric, single-sector, and multisectoral emission reductions. They aim to provide a clear picture of the benefits of state-level and regional policies targeted at air pollution mitigation, as well as the substantial climate co-benefits of lowering black carbon emissions over the IGP. The emission-reduction scenarios used in this study, along with their rationale, are listed in Table 1.

Table 1: *Emission-reduction scenarios for black carbon in the IGP used in the study*

Emission-reduction scenarios	Emission sector (percentage reduction)	Region	Rationale
Scenario 1	Agricultural waste burning (50%)	Punjab and Haryana	Multiple policies support both ex situ and in situ management of crop residues, including financial incentives. The Commission for Air Quality Management in the National Capital Region and Adjoining Areas (CAQM) has issued seven notifications. Additional enabling policies include mandating 5%–10% co-firing in power plants (CAQM, 2021). CAQM and other stakeholders have claimed a 70% reduction in Punjab alone (MoEFCC, 2022), with larger reductions in NCR districts (Ministry of Environment, Forest and Climate Change, 2025). Therefore, this scenario assumes a net 50% reduction in crop residue burning across the region.
Scenario 2	Transport (50%)	National Capital Region (NCR)	The CAQM and the Government of the National Capital Territory (NCT) Delhi have notified and implemented numerous ambitious policies to reduce transport emissions. These include a ban on older vehicles, restrictions on freight entry, electrification of the older bus fleet, near-removal of diesel buses and autos, and the requirement that only Bharat Stage VI (BS VI) vehicles be allowed under the Graded Response Action Plan (GRAP).

Emission-reduction scenarios	Emission sector (percentage reduction)	Region	Rationale
Scenario 3	Energy (50%)	IGP	This scenario is based on existing mandates for flue gas desulphurisation (FGD) installation in NCR power plants (Ministry of Environment, Forest and Climate Change, 2022); requirements for co-firing using agricultural residues (5%–10%); and the presence of multiple biomass-fired power plants across the region (CAQM, 2021).
Scenario 4	Open waste burning (90%)	IGP	The Swachh Bharat Mission targets open waste burning. All 37 non-attainment cities have bylaws for municipal waste management (Ministry of Housing and Urban Affairs, 2021). This is considered an achievable target because enabling conditions are largely in place.
Scenario 5	Transport (50%)	IGP	All states in the IGP have electric vehicle policies with ambitious targets. Additionally, India has leapfrogged from BS IV to BS VI emission standards (Ministry of Road Transport and Highways, 2016). While action has been most pronounced in Delhi, more needs to be done across the IGP. Therefore, this scenario may be treated as ambitious.
Scenario 6	Domestic (60%)	Bihar	Bihar ranks third among all states in total Pradhan Mantri Ujjwala Yojana (PMUY) connections, with 37.90 lakh connections as of 2024–25 (Ministry of Petroleum and Natural Gas, 2025). The state has about 230.4 lakh active domestic LPG customers (Petroleum Planning & Analysis Cell, 2026). Bihar has made considerable progress in increasing LPG connections and promoting clean cooking initiatives. Therefore, this scenario assumes a net 60% reduction in domestic-sector emissions in Bihar.
Scenario 7	Industry (50%)	IGP	The IGP has significant economic activity, with many large and medium-sized enterprises reliant on the region's agricultural output. These include brick kilns, agro-based industries, chemicals, textiles, sugar mills, rice mills, steel-processing units, rolling mills, and jute mills in the eastern parts of the region. While almost all states have approved fuel policies (Government of National Capital Territory of Delhi, Environment Department, 2018; Government of West Bengal, Department of Environment, 2020; Haryana State Pollution Control Board, 2022; Government of Punjab, Department of Science, Technology and Environment, 2023), and there is substantial compressed natural gas (CNG) penetration, most industries remain dependent on fossil fuels. This scenario is based on current rates of CNG and piped natural gas (PNG) adoption and the approved fuel policies across these states.

<table>
<tr><th>Emission-reduction scenarios</th><th>Emission sector (percentage reduction)</th><th>Region</th><th>Rationale</th></tr>
<tr><td>Scenario 8</td><td>Domestic (60%)</td><td>Uttar Pradesh</td><td>Uttar Pradesh has one of the highest rates of clean fuel adoption for cooking and heating. The state has the highest number of PMUY connections, at 56.88 lakh (Ministry of Petroleum and Natural Gas, 2025). It has also invested in the airshed approach through multilateral loans, and there is a major push to reduce domestic emissions. These efforts include the Uttar Pradesh Clean Air Management Programme (UP CAMP), under which clean cookstoves have been distributed.</td></tr>
<tr><td>Scenario 9</td><td>Domestic (50%)</td><td rowspan="2">IGP</td><td>Most global emission inventories identify domestic emissions as the major source of pollution in the region. There has also been considerable political will and policy support for clean cooking initiatives. Therefore, this scenario considers the combined impact of a 50% reduction in domestic-sector emissions across IGP states.</td></tr>
<tr><td>Scenario 10</td><td>Agricultural Waste Burning (50%), Transport (50%), Energy (50%), Open Waste Burning (90%), Domestic (50%), Industry (50%)</td><td>This combined scenario assesses the cumulative efficacy of interventions across the specified sectors. Ambitious reduction values are used to estimate the maximum possible reduction if appropriate policies are notified and effectively implemented.</td></tr>
</table>

3. Results and Discussion

This chapter presents the results of the REACH modelling analysis, beginning with model validation, followed by the impacts of the emission-reduction scenarios on black carbon concentrations and the associated health and climate co-benefits. Methodological considerations relevant to the interpretation of the findings are discussed in the final section.

3.1. Model validation

The REACH model, run with unperturbed total emissions, provides an annual average $PM_{2.5}$ concentration for each model grid cell. For model validation, annual average $PM_{2.5}$ observations from the Central Pollution Control Board's (CPCB) CAAQMS network are used. Modelled $PM_{2.5}$ concentrations are extracted at the grid centroid nearest to the CAAQMS monitoring locations, based on latitude and longitude, for comparison. Model performance is validated using multiple statistical metrics provided in Annexure 3.

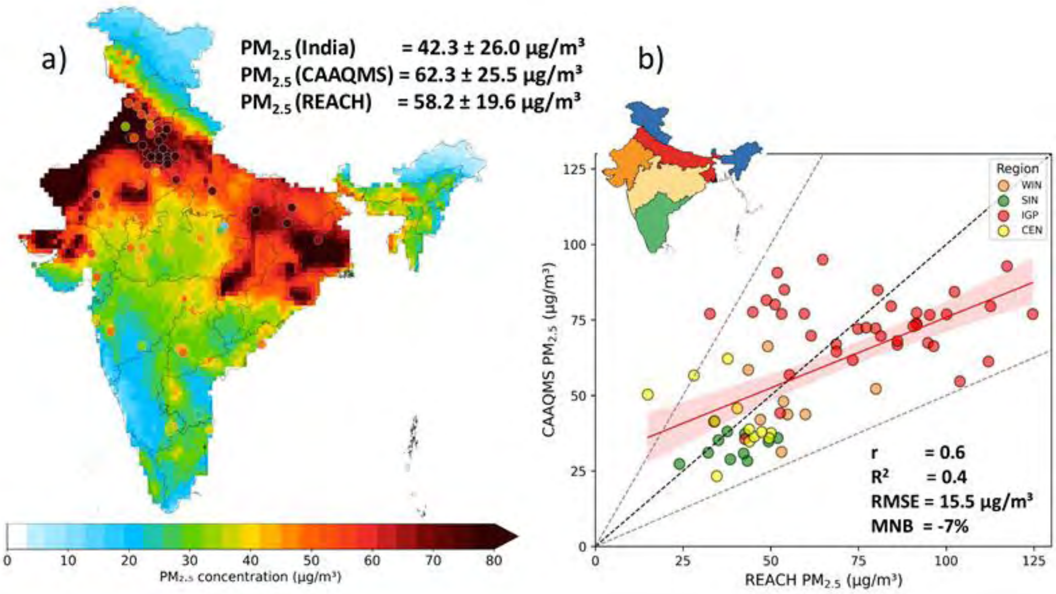
Figure 3(a) presents the spatial distribution of annual average $PM_{2.5}$ concentration across India as simulated by the REACH model. Overall, the model captures the major pollution hotspots, with a national annual $PM_{2.5}$ concentration of 42.2 μg/m^3.

REACH estimates fall within the range of prior studies and are closer to satellite-derived values than some ground-based estimates. The annual average population-weighted $PM_{2.5}$ concentration is 48.3 μg/m^3 for 2019, which is comparable to the satellite-derived $PM_{2.5}$ concentration of 57.3 μg/m^3, 5th–95th percentile, reported by Dey et al. (2020). However, our estimate is higher than the 32.8 μg/m^3 reported by Guo et al. (2018) for 2015 and lower than the 74.3 μg/m^3 reported by HEI (2018) for 2015. At the CAAQMS sites, the average REACH-predicted concentration ['$PM_{2.5}$ (REACH)'] of 58.2 μg/m^3 shows good agreement, with a -6.5% bias, with the average CAAQMS concentration of 62.3 μg/m^3 ['$PM_{2.5}$ (CAAQMS)'].

High annual average $PM_{2.5}$ concentrations, exceeding 80 μg/m^3, are observed across the IGP, Chhattisgarh, Jharkhand, Rajasthan, and Gujarat. Over the IGP, the 5th-percentile $PM_{2.5}$ concentration is 43.2 μg/m^3. Relatively lower annual mean $PM_{2.5}$ concentrations, with 5th–95th percentile, ranging from 12.3 μg/m^3 to 57.1 μg/m^3, are observed in other regions of India.

Figure 3(b) shows a scatter plot comparing modelled and observed $PM_{2.5}$ concentrations across different regions of India. The model shows moderate agreement with observations, with a correlation coefficient of 0.6. Such performance is typically considered good for the Indian region (Shandilya et al., 2024). The model exhibits an overall underestimation, with a mean normalised bias of -7% relative to CAAQMS observations. This underestimation is higher in regions with higher $PM_{2.5}$ concentrations, such as the IGP.

__Figure 3:__ Validation of REACH-simulated $PM_{2.5}$ concentration against observed $PM_{2.5}$ concentration over India (a) Spatial distribution of annual average $PM_{2.5}$ concentrations across India, with CAAQMS monitoring locations overlaid.



Notes: $PM_{2.5}$ (India) represents the area-weighted average REACH-simulated $PM_{2.5}$ concentration; $PM_{2.5}$ (REACH) represents the average REACH-simulated $PM_{2.5}$ concentration at the filtered CAAQMS locations; and $PM_{2.5}$ (CAAQMS) represents the average observed $PM_{2.5}$ concentration at the same CAAQMS locations.

WIN: West India, SIN: South India, IGP: Indo-Gangetic Plain, CEN: Central India.

3.2. Black carbon reduction under emission scenarios

This section discusses the air quality impacts of 10 emission-reduction scenarios on black carbon and $PM_{2.5}$ concentrations.

3.2.1. IGP-wide impacts

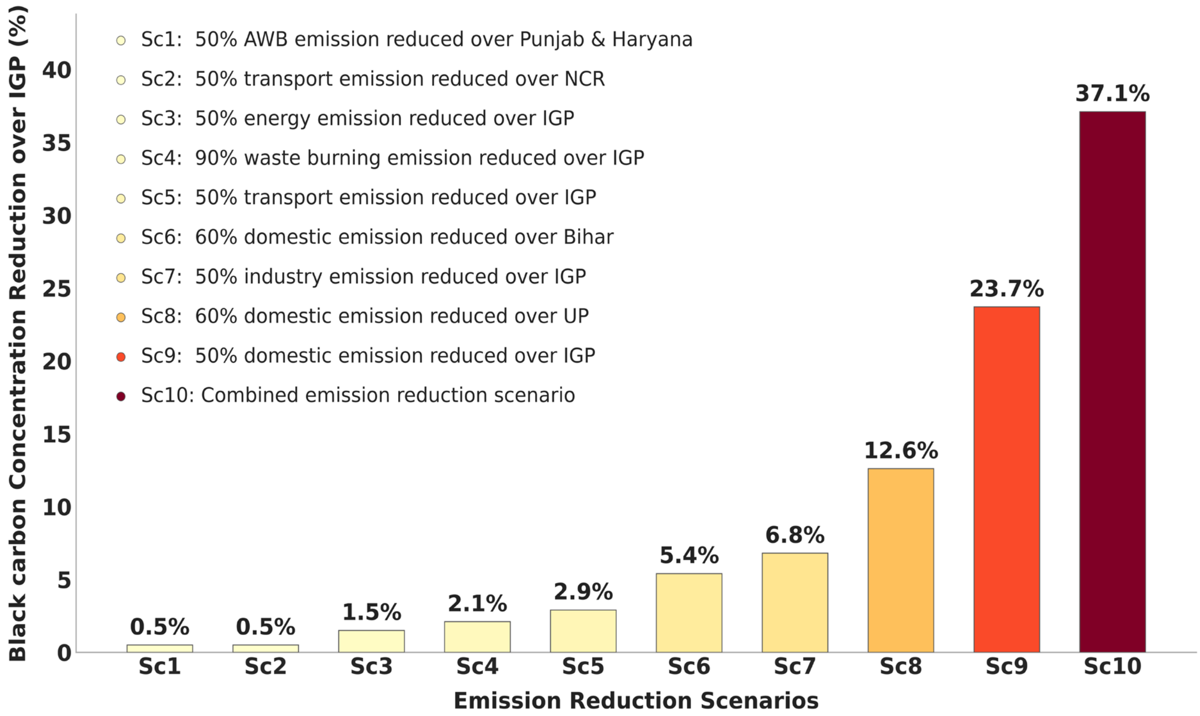
Figure 4 depicts improvements in air quality as percentage reductions in black carbon concentration over the IGP in response to the emission-reduction scenarios. The baseline concentrations of black carbon and $PM_{2.5}$ across the region are 2.55 µg/m³ and 63.1 µg/m³, respectively. The corresponding black carbon and $PM_{2.5}$ concentrations for the emission-mitigation scenarios are provided in Annexure 2.

Overall, Scenario 10 provides the largest decrease in black carbon concentration, approximately 37%, over the IGP. This scenario represents emission reductions of at least 50% from all major sources across the IGP. The black carbon concentration under this scenario is 1.6 µg/m³, with a corresponding $PM_{2.5}$ concentration of 62.16 µg/m³.

The second-most effective scenario, Scenario 9, halves emissions from the largest source, the domestic sector, across the IGP and results in a 23.7% reduction in black carbon concentration. Under this scenario, black carbon concentration is 1.95 µg/m³, while $PM_{2.5}$ concentration is 62.50 µg/m³.

Mitigating half of the emissions from industry (Scenario 7), energy (Scenario 3), and transport (Scenario 5) leads to reductions of 6.8%, 1.5%, and 2.9% in black carbon concentrations, respectively. Although industry, energy, and transport are among the highest black carbon–emitting sectors, their contributions are substantially lower than those of domestic sources. Mitigating emissions from open waste burning (Scenario 4) over the IGP results in a 2.1% decrease in black carbon concentrations.

Figure 4: *Percentage reduction in black carbon concentration over the IGP under the corresponding emission-reduction scenarios.*

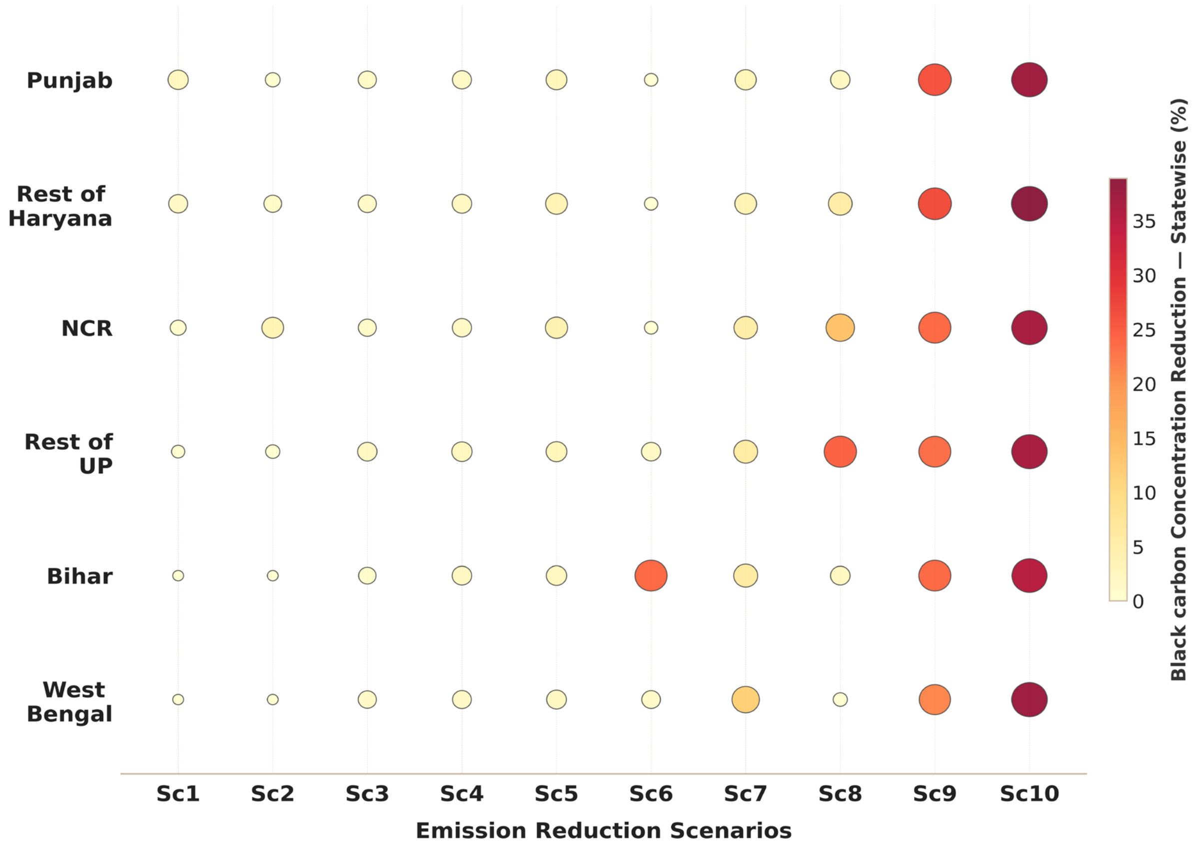


3.2.2. State-wise impacts

Along with assessing the impact of the emission-reduction scenarios across the IGP, a state-wise evaluation is important to identify the most and least benefited states, as illustrated in Figure 5. The symbol size represents the magnitude of the reduction of black carbon concentration.

Among the scenarios, Scenario 10 is the only one that adopts a multisectoral approach targeting the major sources of black carbon emissions across the region. This results in significant reductions in black carbon emissions and an approximately 25%–35% reduction in black carbon concentrations across the IGP states.

Figure 5: *State-wise percentage reduction in black carbon concentration under the corresponding emission-reduction scenarios.*



The remaining scenarios focus on prioritising one emission source at a time. The state-wise impacts are discussed below:

- **Punjab**: Approximately 26% of Punjab's black carbon concentration is reduced under Scenario 9, which assumes a 50% reduction in black carbon emissions from the domestic sector across the IGP. If emissions from agricultural waste burning are reduced by half, black carbon concentration decreases by 2.4%.

- **Rest of Haryana**: As in Punjab, a 26% reduction in black carbon concentration is achieved under Scenario 9. Lowering transport emissions across the NCR and the IGP leads to 1.1% and 3.6% reductions in black carbon concentration, respectively, whereas reducing agricultural waste burning by half yields a 1.2% reduction. Hence, reducing domestic emissions across the IGP should remain the top priority.

- **National Capital Region (NCR)**: Targeting the transport sector across the NCR and the IGP reduces black carbon concentration by around 3.6% and 4%, respectively. However, the maximum benefit is achieved under Scenario 9, which results in a 12% decrease in black carbon concentration in the NCR.

- **Rest of Uttar Pradesh**: Decreasing black carbon emissions from the domestic sector within the state, as in Scenario 8, leads to a 24.4% reduction in the state's black carbon concentration. A similar reduction is seen when domestic emissions are reduced across the IGP under Scenario 9.

- **Bihar**: Apart from Scenario 10, Bihar's air quality, in terms of black carbon concentration, can be improved under Scenarios 6 and 9. Scenario 6 reduces black carbon emissions from the domestic sector in Bihar alone, while Scenario 9 reduces domestic-sector emissions across the entire IGP. Both scenarios result in an approximately 23% reduction in black carbon concentration with respect to the baseline.

- **West Bengal**: Here too, reducing domestic-sector emissions across the IGP under Scenario 9 provides the maximum improvement, reducing the state's black carbon concentration by 21%. In addition, reducing industrial emissions across the IGP leads to an 11.5% reduction in black carbon concentration in the state. This is likely due to the presence of heavy industry, steel plants, and rolling mills in the region, many of which currently depend on coal.

The state-wise assessment highlights three key findings. First, the domestic sector contributes the majority of the IGP's black carbon emissions. Second, among single-source emission-reduction scenarios, reducing emissions from the domestic sector yields the greatest air quality benefits both at the state level and across the IGP region. Third, longer-term air quality improvements will require targeting year-round emissions from sectors such as domestic energy use, industry, and transport.

3.3. Health impacts

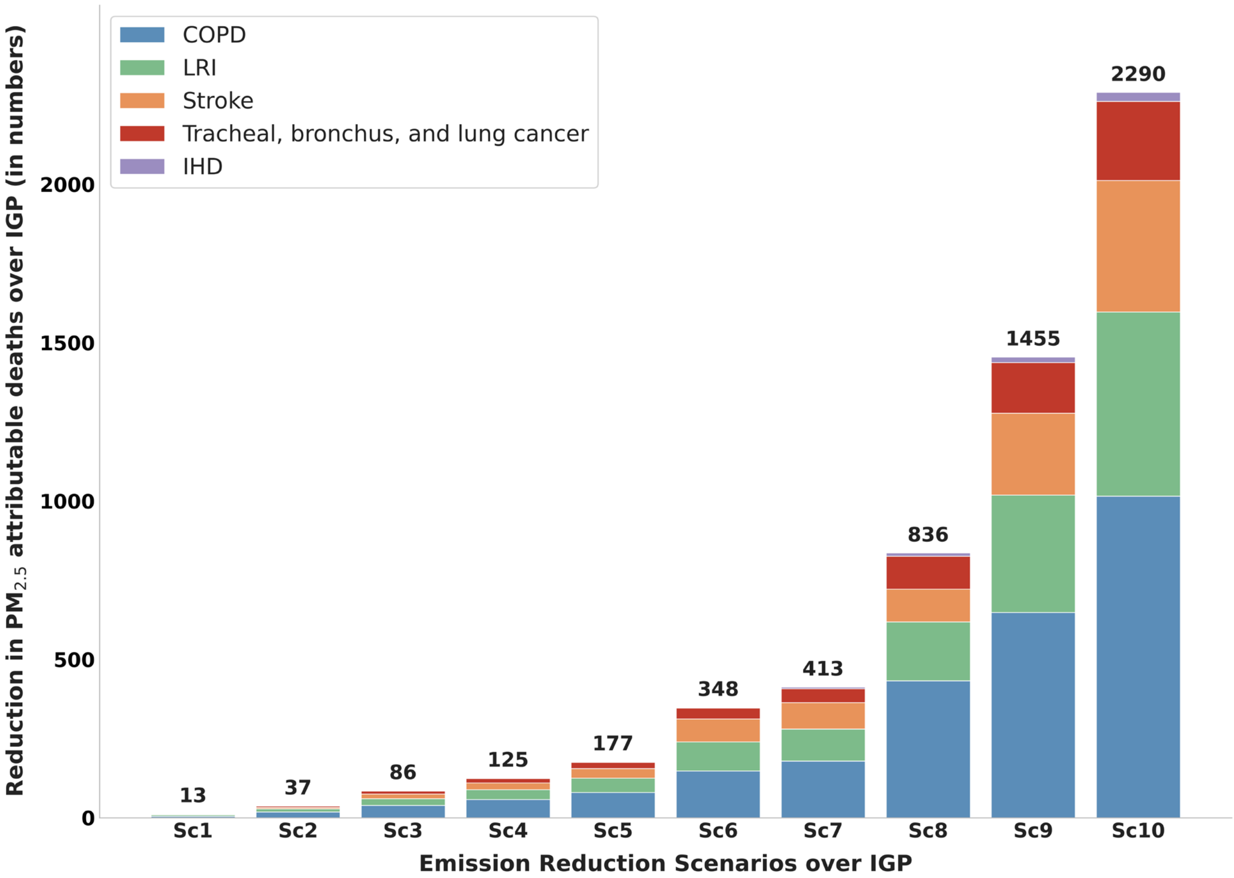
The health impacts are presented as avoided $PM_{2.5}$-attributable mortality burden in response to the air quality benefits associated with emission-reduction scenarios (Figure 6). A 50% reduction in domestic-sector emissions across the IGP airshed could reduce the $PM_{2.5}$-associated mortality burden by 1,455 premature deaths. **The multisectoral airshed approach (Scenario 10) could avoid an additional 835 $PM_{2.5}$-attributable premature deaths.**

The avoidable $PM_{2.5}$-attributable mortality burden under all other emission scenarios is less than 500, except for Scenario 8, which avoids 836 $PM_{2.5}$-attributable premature deaths in the IGP. Across all the scenarios, the maximum reduction is observed in COPD-related deaths, while reductions in premature deaths caused by LRIs and stroke are consistently among the top three health benefits.

These findings suggest that mitigating one of the key constituents of $PM_{2.5}$ can produce a considerable reduction in $PM_{2.5}$-attributable mortality in the region. Owing to the region's dense population, even moderate improvements in air quality can yield substantial health benefits.

It is important to note that the mortality burden in this study is estimated based on reductions in total $PM_{2.5}$ concentrations rather than black carbon-specific concentrations. Consequently, the assessment does not explicitly account for the toxicity of black carbon. The mortality benefits reported here may, therefore, represent conservative estimates of the true health benefits of black carbon mitigation.

Figure 6: Reduction in $PM_{2.5}$-attributable mortality burden over the IGP under the corresponding emission-reduction scenarios.



3.4. Climate co-benefit assessment for emission-reduction scenarios

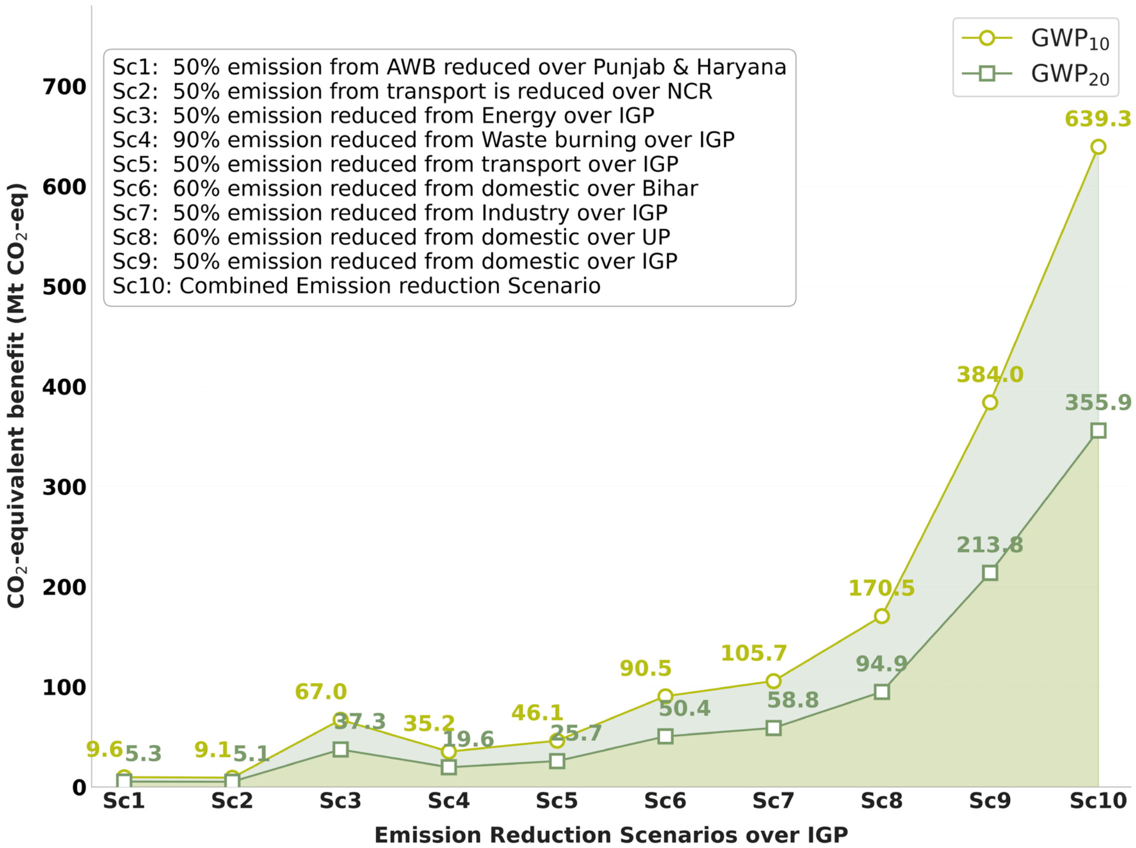
This section discusses the climate co-benefits associated with mitigating black carbon emissions. To understand the benefits of black carbon mitigation, CO_2-equivalent benefits and changes in radiative forcing are analysed for each emission-reduction scenario. The CO_2-equivalent metric quantifies the climatic benefit of black carbon mitigation by equating it to CO_2 removal in a given period. The change in radiative forcing shows the decrease in energy absorption in the Earth–atmosphere system due to reduced black carbon emissions.

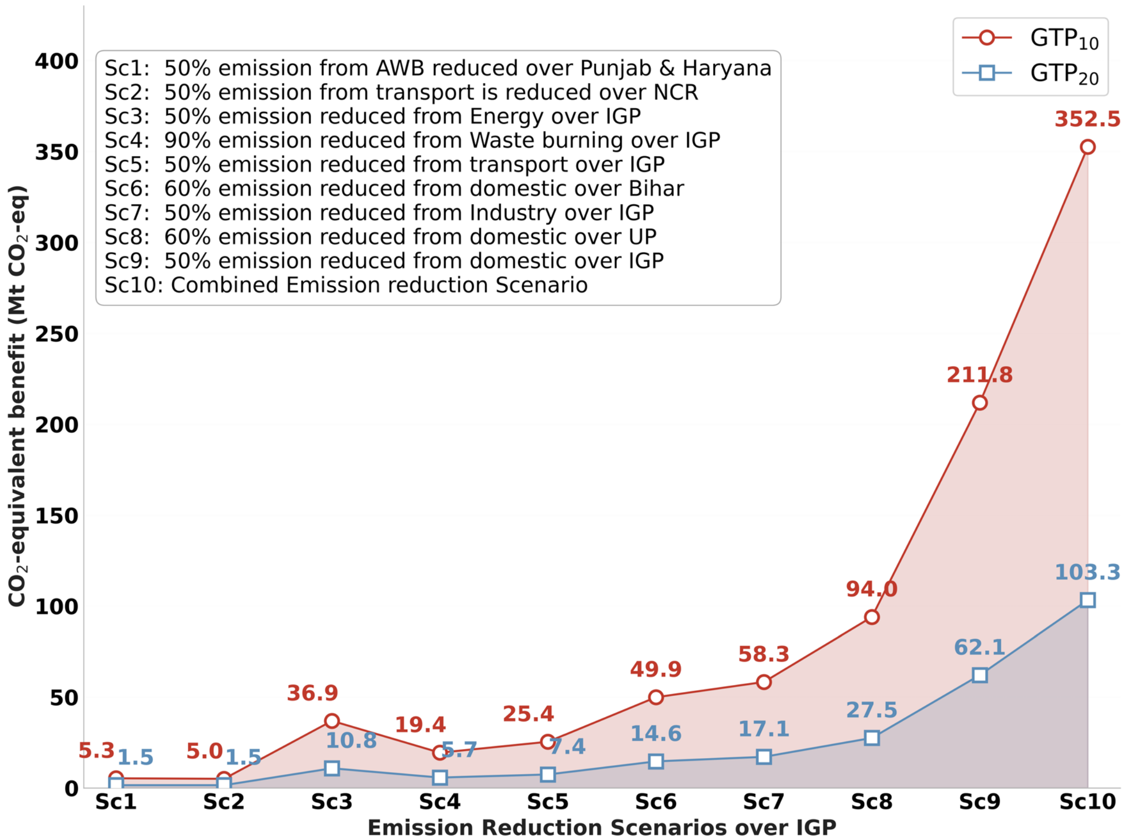
3.4.1. CO_2-equivalent benefits

The CO_2-equivalent benefits of black carbon mitigation across the 10 emission-reduction scenarios are shown in Figure 7. These benefits are estimated using climate metrics such as GTP and GWP. The scenario that provides the largest emission reduction yields the greatest climate co-benefits.

Scenario 10 mitigates 147 kt of black carbon across the IGP, corresponding to a climate benefit equivalent to 639 million tonnes (Mt) of CO_2 based on GWP10 and 352 Mt of CO_2-equivalent based on GTP10. Scenario 9 yields climate co-benefits equivalent to 384 Mt CO_2-equivalent based on GWP10 and 211.8 Mt CO_2-equivalent based on GTP10.

Figure 7: CO_2 equivalent benefit estimated from avoided black carbon emissions for each emission-reduction scenario using climate metrics, (A) GWP and (B) GTP, for 10- and 20-year time horizons.





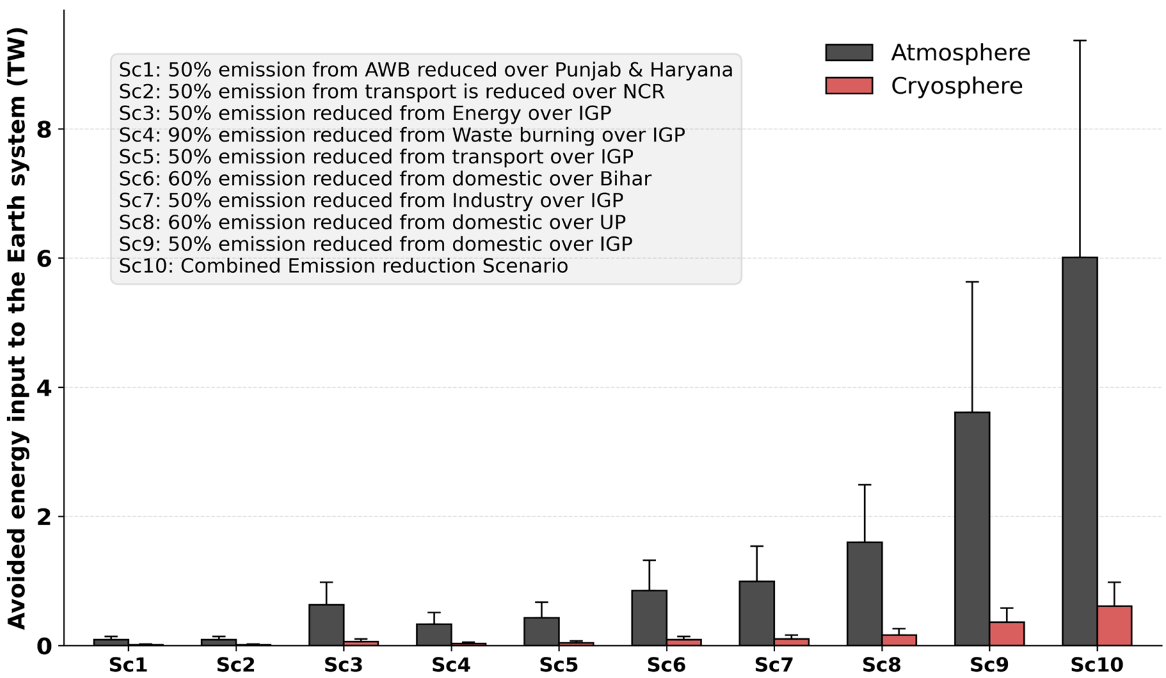
The climatic effect of black carbon is strongest over shorter time horizons and decreases over time. For Scenario 10, GWP20 is 44% lower than GWP10, while GTP20 is approximately 70% lower than GTP10. Nevertheless, even over a 20-year horizon, emission reductions under Scenario 10 deliver substantial climate co-benefits equivalent to the removal of 356 Mt CO_2 based on GWP20 and 103 Mt CO_2 based on GTP20.

3.4.2. Change in radiative forcing

The avoided energy absorption resulting from reduced black carbon emissions under each emission-reduction scenario is shown in Figure 8. Multisectoral emission reductions under Scenario 10 decrease atmospheric energy absorption by approximately 6 terawatts (TW). Over the cryosphere, Scenario 10 limits energy absorption by approximately 0.6 TW. The reduction in additional energy input to the Earth–atmosphere system is evaluated over a one-year period.

Scenario 9 results in a 3.6 TW reduction in atmospheric energy absorption. Furthermore, reducing emissions from the largest black carbon source by half in Uttar Pradesh leads to approximately 1.6 TW less atmospheric energy absorption globally.

Figure 8: *Energy addition to the Earth system (in TW) avoided over one year due to abated black carbon emissions under the corresponding emission-reduction scenarios.*



The climate co-benefit results highlight three key findings:

1. A multisectoral and multi-state approach to reducing black carbon emissions, as represented by Scenario 10, yields approximately 66% larger CO_2-equivalent benefits based on GTP10 and GWP10 than the single-sector approach represented by Scenario 9. It also achieves an additional reduction of approximately 2.4 TW in atmospheric energy absorption.

2. The climate co-benefits of mitigating black carbon are strongest in the near term, as reflected in the CO_2-equivalent benefits estimated using GTP10 and GWP10.

3. Although black carbon emissions are concentrated within regional hotspots, mitigating emissions in major hotspots such as the IGP can generate climate benefits globally.

3.5. Methodological considerations

The results presented above provide robust estimates of the potential benefits of black carbon mitigation over the IGP. However, as with any modelling study, the findings are subject to methodological assumptions and data limitations, which are discussed below.

The REACH model uses a Gaussian plume dispersion framework to increase computational efficiency. The model involves assumptions such as the exclusion of topographic features, reliance on simplified atmospheric stability classes, absence of surface roughness parameterisation, limited representation of long-range transport, and simplified pollutant chemistry. Correction factors are applied to reduce these structural constraints. However, because $PM_{2.5}$ speciation data are unavailable in India, the correction factors used in this study are the same as those used in the REACH model developed for the USA.

REACH is an annual-average reduced-complexity model, which may lead to the underestimation of short-term variability and episodic pollution events. However, this limitation may be less relevant for long-term decision-making. One of the primary source of uncertainty in air quality modelling are emissions. India currently does not have a publicly available national emissions inventory for air pollutants, as of December 2025. Therefore, global emissions inventories were the only available option for this study. However, these inventories are not validated using local ground surveys and can vary substantially across datasets and version updates. For example, for black carbon emissions in India, the Emissions Database for Global Atmospheric Research–Hemispheric Transport of Air Pollution (EDGAR-HTAP) estimate is about 9% lower than the CEDS estimate, while EDGAR version 6 is about 26% lower. Similar discrepancies exist at the sectoral level. Domestic emissions are consistently identified as the largest source of black carbon emissions in India across all three emission inventories; however, domestic emissions in EDGAR-HTAP and EDGAR are lower than those in CEDS by 33% and 57%, respectively. The 2019 base year was chosen because of dataset availability; however, as an older base year, it does not reflect more recent emission trends.

The global emissions inventory used in this study lacks finer activity data. For example, it does not provide information on the age and technology of different power plant units. Similarly, the emissions inventory used to represent agricultural waste burning is available only at a coarse spatial resolution of 25 km. Identifying the locations of individual burning events is difficult and would require substantial assumptions. Hence, the absence of fine-scale activity data for emission sectors restricts the design of location- or event-specific reduction scenarios.

4. Policy Implications

This chapter reviews existing international, national, regional, and state-level policies that have already delivered climate co-benefits through reductions in black carbon and other SLCPs. It also identifies gaps that limit these benefits and outlines practical pathways for maximising co-benefits through existing institutional structures. These are in addition to the ongoing initiatives to reduce $PM_{2.5}$ under India's National Clean Air Program (NCAP). Annexure 4 maps the policies that enable climate and air quality co-benefits.

4.1. Existing policies delivering climate co-benefits

Although most existing air quality and sectoral policies in India do not officially recognise black carbon as an emissions target, they generally address $PM_{2.5}$ emissions from combustion-related sources, in which black carbon is a significant climate-active component. Therefore, regulations and policies targeting $PM_{2.5}$ pollution can deliver climate co-benefits by reducing black carbon. Conversely, mitigation of other SLCPs, such as ozone, can also impact $PM_{2.5}$ levels, even when climate mitigation is not an explicit objective.

4.1.1. International treaties

At the international level, climate and air quality governance frameworks have increasingly moved towards integrated approaches, co-benefits, and flexibility in mitigation pathways, increasing the policy relevance of black carbon and SLCPs.

- **The Paris Agreement** (2015) enables parties to undertake mitigation actions consistent with sustainable development objectives and broader public health co-benefits. Although the treaty does not specifically address black carbon, its mitigation regime under Articles 2(1)(a) and 4 promotes the reduction of greenhouse gas emissions, which can also lower combustion-related co-pollutants such as black carbon. This can facilitate near-term climate benefits alongside air quality improvements (UNFCCC, 2015).

- **World Health Organisation (WHO) Air Quality Guidelines (2021)** introduce more stringent, health-based standards for $PM_{2.5}$ and PM_{10} concentrations. Given that black carbon represents a significant fraction of $PM_{2.5}$ in numerous urban and rural environments, particularly in South Asia, full adherence to these guidelines could enable substantial reductions in black carbon exposure levels. This would have major public health benefits, along with related climate co-benefits (WHO, 2021).

Taken together, these international agreements provide a strong scientific and policy foundation for regional efforts towards public health protection and near-term climate mitigation, even though they do not include explicit black carbon targets.

4.1.2. National policy context

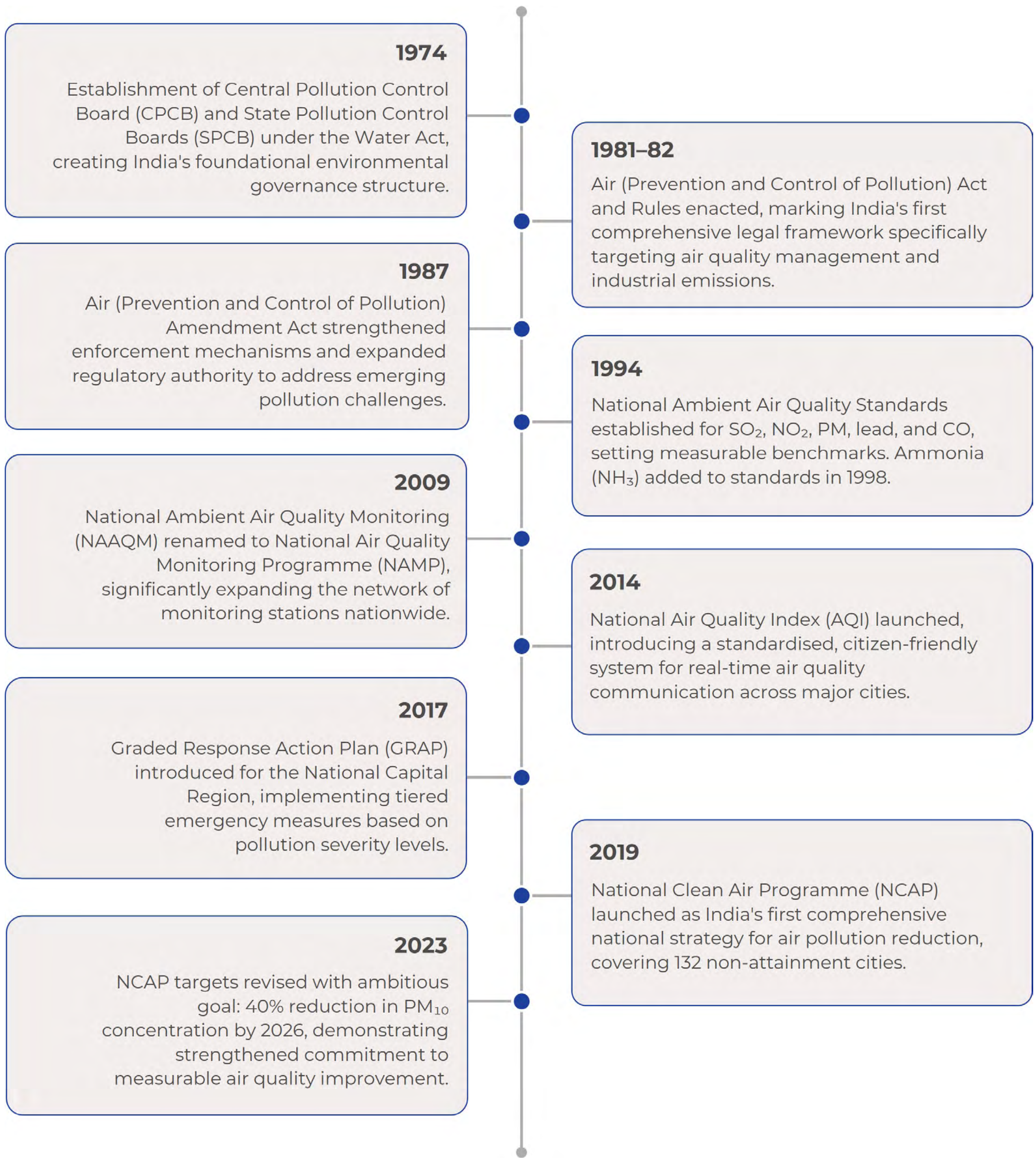
India's national air quality governance framework has progressively evolved through legislation, standards, monitoring systems, and targeted programmes that primarily address air pollution and public health while generating important climate co-benefits through reductions in black carbon and other SLCPs.

As illustrated in Figure 9, the institutional foundations were established with the creation of pollution control authorities in 1974, followed by the Air (Prevention and Control of Pollution) Act, 1981, amended in 1987. The Act remains the principal legal framework regulating air pollution in the country. It empowers the CPCB to set emission standards and regulate emissions from major combustion-related sectors, including transport, industry, residential energy use, waste burning, and agriculture.

The introduction of the National Ambient Air Quality Standards (NAAQS) in 1994, later expanded to include additional pollutants, strengthened regulatory control over particulate matter, including $PM_{2.5}$ and PM_{10}, which contain significant fractions of black carbon emitted from incomplete combustion processes. The expansion of monitoring networks under the National Air Monitoring Programme (NAMP) and the launch of the Air Quality Index (AQI) in 2014 further improved air quality assessment and public communication.

More recent policy initiatives have adopted programme-based approaches. The GRAP, introduced in 2017, established emergency pollution-control measures targeting transport, construction, industry, and waste burning during severe pollution episodes. Subsequently, the NCAP, launched in 2019, established a coordinated national strategy addressing emissions from urban and sectoral sources, with revised targets aiming for up to a 40% reduction in PM_{10} concentrations by 2025–26.

Figure 9: *Evolution of air quality regulations in India.*



National initiatives also contribute sector-specific air quality improvements and climate co-benefits through reductions in $PM_{2.5}$ emissions, of which black carbon forms an important fraction. In the residential sector, the expansion of clean cooking access under the PMUY and PMUY 2.0 has accelerated the transition away from biomass-based household fuels, while programmes such as the National Biogas and Manure Management Programme and the Unnat Chulha Abhiyan (2014) promote cleaner combustion technologies. Regulatory actions restricting high-emitting fuels, including nationwide controls on pet coke and furnace oil issued by the CPCB and the National Green Tribunal (2019), further reduce combustion-related particulate emissions. Complementary waste-sector interventions under the Swachh Bharat Mission and the Solid Waste Management Rules, 2016, along with agricultural measures such as the Crop Diversification Programme under the Rashtriya Krishi Vikas Yojana and the Central Sector Scheme for In-Situ Crop Residue Management (Ministry of Agriculture and Farmers' Welfare , 2020), address open burning sources that contribute substantially to seasonal $PM_{2.5}$ and black carbon emissions.

Similarly, policies in the industrial, transport, and energy sectors operationalise emission reductions through technology and fuel transitions rather than explicit climate mandates. The adoption of cleaner production pathways is supported through instruments such as the National Steel Policy (2017), which promotes electric arc and induction furnaces; updated emission standards for brick kilns under the Ministry of Environment, Forest and Climate Change (MoEFCC) Notification GSR 143(E), 2022; and pollution-control requirements for thermal power plants under the revised MoEFCC emission standards (2015). In the transport sector, the implementation of BS-VI Emission Standards (2020), vehicle electrification incentives under Faster Adoption & Manufacturing of Electric vehicles (FAME I and II), the Electric Mobility Promotion Scheme (2024), and vehicle scrappage measures under the Voluntary Vehicle Fleet Modernisation Programme collectively target high-emitting sources. For diesel generators, CPCB introduced emission norms under GSR 804(E), 2023, which contribute to reductions in combustion-derived particulate matter. These measures are primarily designed to improve air quality, targeting sectors that emit soot and $PM_{2.5}$. Abating emissions from these sectors can lead to substantial reductions in black carbon concentrations.

In aggregate, these national policies and initiatives demonstrate that India's clean air strategies can also deliver climate co-benefits, even though such benefits are not always explicitly recognised or reported (UNEP, 2021). The focus should therefore not be on the absence of policy tools but on increasing the visibility of the climate relevance of existing air quality measures through improved monitoring and reporting under current governance frameworks.

4.1.3. State level: Punjab and other IGP states

At the state level, the implementation of national policies and state-specific initiatives plays a critical role in realising climate co-benefits. Punjab is an important region in the IGP because of its agricultural practices and seasonal influence on regional air quality.

Punjab's State Action Plan on Climate Change (SAPCC) integrates mitigation and adaptation measures in key sectors such as energy, agriculture, transport, and urban development (Government of Punjab, 2014). Although black carbon is not specifically listed, these sectors are major sources of combustion-related emissions. The implementation of NCAP city action plans in Punjab's non-attainment cities has been tailored to address transport emissions, industrial discharges, road dust, and open waste burning, with the explicit objective of mitigating fine particulate pollution (MoEFCC, 2019).

Crop residue management remains one of the most important policy interventions in Punjab from a climate co-benefits perspective. The state has adopted large-scale mechanisation support programmes to promote in-situ and ex-situ residue management technologies, such as Happy Seeders and Super Seeders, along with subsidies and strict enforcement to control open burning. This has reportedly reduced seasonal emissions during the post-monsoon period (Ministry of Agriculture and Farmers Welfare, 2023; Government of Punjab, 2022) by reducing the practice of residue burning, thereby lowering episodic black carbon emissions.

Punjab has made significant strides towards controlling industrial emissions. The city of Mandi Gobindgarh has issued notifications to transition entire industrial clusters to cleaner fuels (NGT Principle Bench, 2025). Industrial emissions in the NCR are also influenced by regulatory directions issued by the CAQM for the NCR and adjoining areas. The CAQM Approved Fuel List effectively restricts the use of high-emitting fuels, namely coal, furnace oil, and pet coke, in industrial operations while promoting cleaner alternatives, including natural gas and electricity (CAQM, 2021). Such a transition to approved fuels increases combustion efficiency and lowers soot production, resulting in lower black carbon emissions from industrial clusters.

Similar policy instruments are being implemented in other IGP states. Haryana and western Uttar Pradesh have established norms to check stubble burning and implement CAQM fuel specifications in NCR districts. These actions are designed to reduce cross-boundary pollution transport within joint airsheds (CAQM, 2022). Districts in Rajasthan that fall within the NCR have also imposed bans and prescribed emission-reduction norms for industrial fuels, in accordance with directions from the State Pollution Control Board.

In the eastern IGP, policy attention towards combustion emissions is gradually expanding. Black carbon is being monitored in Bihar as part of its State Action Plan for Prevention and Control of Air Pollution, recognising its importance for both climate and health impacts (Bihar State Pollution Control Board, 2023). This is an important case study of subnational acknowledgement of SLCPs in air quality management. Similarly, West Bengal has strengthened its rules on industrial emissions and improved municipal solid waste management to reduce open burning and, consequently, particulate emissions (West Bengal Pollution Control Board, 2020).

Together, these state-level actions demonstrate that air quality policy in Punjab and the wider IGP is already enabling climate co-benefits. Although these measures primarily focus on pollution reduction and improved public health, they also reduce combustion-related emissions, which is critical for slowing the warming effects of black carbon and other short-lived climate pollutants.

4.2. What is missing in current policies

Despite this strong policy foundation, several gaps limit the ability of existing frameworks to fully capture and maximise climate co-benefits from reductions in black carbon and other SLCPs.

First, black carbon is rarely identified as an explicit policy target. It does not find mention in the NCAP or India's Nationally Determined Contributions (NDCs). Most regulations target PM_{10} and $PM_{2.5}$ mass without distinguishing between their components, even though these components can have very different climate-forcing potentials. Further, given the current design of the NCAP, most on-ground actions by cities target PM_{10} and focus more on dust-related sources. As a result, the most important combustion sources of black carbon are often not prioritised in policy measures.

Second, black carbon is not monitored regularly. While $PM_{2.5}$ monitoring networks have expanded substantially, black carbon or elemental carbon measurements are not part of standard regulatory monitoring. This limits the ability to monitor trends, evaluate the impact of interventions, and link air quality improvements with climate impacts.

Third, monitoring, reporting, and verification systems focus on activities and corresponding expenditure rather than outcomes. State-level reporting often tracks inputs, such as the number of machines installed or inspections carried out, rather than whether actual emission reductions and climate benefits have been achieved.

Fourth, enforcement of regulations remains uneven, particularly for open agricultural burning, informal industrial sources, and waste burning. Weak enforcement reduces the realised air quality and climate benefits of existing policies.

Finally, policy planning and evaluation remain largely city- or state-centric, whereas black carbon impacts operate at the airshed scale. This is not due to the absence of an airshed-level institution. The CAQM is a statutory body with powers to mandate sectoral actions across state boundaries. It has used these powers to issue directives on mitigation measures for crop residue burning, industrial fuels, and vehicular emissions. The limitation lies instead in its reach and implementing powers. The CAQM's jurisdiction extends only to the NCR and adjoining areas. Much of the IGP, therefore, falls outside any comparable airshed-level mandate, including eastern Uttar Pradesh, Bihar, West Bengal, parts of Haryana, and large parts of Punjab. Even within CAQM's jurisdiction, implementation across states remains uneven. Financial resources and implementation mechanisms remain under the purview of the state governments. These limitations reduce the effectiveness of individual state actions and leave shared climate benefits across the wider IGP unrealised.

Co-aligning NDC implementation with NCAP actions would allow air quality improvement to be recognised as a critical element of near-term climate mitigation, especially in highly polluted regions such as the IGP.

4.3. How existing policies can be strengthened to enhance climate co-benefits

Addressing these gaps does not require the creation of new policy structures. Rather, climate co-benefits can be enhanced with incremental improvements to current frameworks that deliver near-term gains.

Climate co-benefits can be strengthened by better integrating black carbon and other SLCPs within existing $PM_{2.5}$ management systems. This can be achieved by introducing selective monitoring of black carbon at representative locations and by tracking emissions from major combustion sources such as transport, industry, and biomass burning. Including these indicators in monitoring, reporting, and verification systems would enable policymakers to identify which interventions deliver the greatest combined air quality and climate benefits.

Linking emission reductions to observed improvements in air quality, health outcomes, and climate metrics would clarify the appropriate balance between local and regional strategies and help prioritise high-impact interventions within existing programmes.

Existing programmes such as the NCAP, SAPCCs, and city clean air action plans provide platforms through which climate co-benefit reporting could be introduced without institutional restructuring.

Finally, enhancing coordination for airshed management between IGP states, while building on existing regional frameworks, would amplify the impact of interventions and maximise shared air quality and climate benefits.

4.4. Aligning Punjab and IGP actions with national and international frameworks: Sector-specific solutions

Punjab and other IGP states are already well-positioned to align their air quality actions with national and international climate frameworks. By explicitly recognising black carbon mitigation as a climate co-benefit within SAPCCs, NCAP reporting, and state action plans, subnational actions can be linked to national climate commitments and international goals without creating new governance structures.

Results from the modelling analysis show that climate and air quality benefits across the IGP are driven largely by interventions targeting year-round combustion sources rather than seasonal emissions alone. The results also show that multisectoral and airshed-level interventions, as represented by Scenario 10, achieve the highest black carbon concentration reduction, at about 37%. In addition, these interventions are the most effective in reducing mortality burden and lead to significant climate co-benefits, estimated at approximately 639 Mt CO_2-equivalent using $GWP_{10.}$

Accordingly, sectoral solutions should prioritise interventions based on emission dominance and demonstrated reduction potential.

1. Residential energy: Highest priority sector

The emission inventory identifies the domestic sector as the largest contributor to black carbon emissions across all IGP states, accounting for more than 60% of regional emissions. The scenario analysis suggests that reducing domestic emissions across the IGP, as in Scenario 9, would lead to an approximately 24% reduction in regional black carbon concentrations, along with substantial public health and climate benefits.

Policy priorities

- Ensure a sustained transition to clean cooking through refill affordability support and behavioural adoption programmes.
- Address biomass burning for heating during winter months in the northern IGP states.
- Promote electric and clean heating options in rural communities.
- Integrate national clean fuel transition targets and household-level fuel use indicators into NCAP city action plans to better capture regional and domestic emission reductions.
- Target efforts in Uttar Pradesh and Bihar, where domestic emissions have the greatest regional spillover.

2. Multisectoral airshed approach: Highest system-level impact

Model results suggest that interventions targeting a single state or sector are insufficient for regional improvement, whereas coordinated emission reductions across multiple sectors and states substantially increase overall benefits. Under Scenario 10, mitigation efforts across domestic, industrial, transport, energy, agriculture, and waste sectors produce the largest climate benefit and avoid nearly 6 TW of atmospheric energy absorption annually.

Policy priorities

- Institutionalise IGP-level airshed management mechanisms.
- Align clean air actions across Punjab, Haryana, Uttar Pradesh, Bihar, and West Bengal.
- Expand the jurisdiction of CAQM beyond NCR districts.
- Adopt joint emission-reduction targets for high-pollution episodes.

3. Industrial and brick kiln transition

Industrial emissions represent the second major source across several IGP states. Scenario results show that a 50% reduction in industrial emissions would lead to an approximately 7% reduction in regional black carbon concentrations. This is particularly important in eastern IGP states, including West Bengal and Bihar, where multiple industrial clusters are located.

Policy priorities

- Accelerate the conversion of traditional brick kilns to zig-zag or cleaner technologies.
- Enforce approved fuel transitions, similar to CAQM directions, across the region.
- Introduce cluster-based emission management for micro, small, and medium (MSME) industrial zones. This may include initiatives such as community boilers, PNG transition, and sustained use of air pollution control devices.
- Link industrial financing and permits with combustion efficiency benchmarks.
- Expand continuous emission monitoring for medium-sized industries.

4. Transport sector: Urban hotspot mitigation

Although transport contributes a smaller regional share of black carbon emissions than domestic sources, state-level analysis shows strong improvements in the NCR and urban clusters when transport emissions are reduced. Transport-focused scenarios produce measurable benefits in Delhi, Haryana, and Punjab because of dense mobility corridors.

Policy priorities

- Accelerate the retirement of high-emitting heavy-duty diesel vehicles.
- Electrify public transport and bus fleets.
- Expand real-world emission compliance monitoring.
- Promote a modal shift towards rail-based freight movement.
- Control emissions from diesel generator dependence in urban areas.

5. Agricultural residue management: Regional episode control

Agricultural burning contributes strongly to seasonal pollution episodes in Punjab and Haryana. While its annual contribution appears smaller, episodic emissions significantly influence regional exposure during post-monsoon months. Scenario results show localised but important improvements under crop-burning reduction strategies.

Policy priorities

- Develop stable biomass markets for residue utilisation.
- Expand biomass co-firing in thermal power plants.
- Incentivise verified non-burning practices.
- Promote crop diversification to reduce the amount of crop residue. Given its fertile soil, the region can support grams, pulses, millets, mustard, and several cash crops.
- Strengthen cross-state coordination during the burning season.

6. Waste management: Low-cost immediate gains

Open waste burning contributes comparatively smaller but avoidable emissions across urban and peri-urban areas. Scenario analysis shows measurable reductions when waste burning is eliminated regionally.

Policy priorities

- Strengthen municipal enforcement of no-burn regulations.
- Expand decentralised composting and biomethanation.
- Integrate informal waste workers into formal collection systems.
- Improve waste segregation at source.
- Explore the possibility of expanding bio-CNG plants that use municipal waste, with one plant in each district.

5. Conclusion and Way Forward

This study demonstrates that black carbon mitigation in the IGP can deliver important air quality, health, and near-term climate benefits. The findings show that domestic-sector emissions are the dominant source of black carbon across the region. Further, an airshed-based, multisectoral approach can deliver the largest combined benefits. Integrating black carbon more explicitly into existing clean air and climate policy frameworks can therefore strengthen ongoing efforts to reduce $PM_{2.5}$ while also enhancing near-term climate mitigation.

To improve future assessments, an up-to-date spatially resolved national-level emissions inventory for air pollutants and short-lived climate pollutants is necessary. Air quality modelling and emissions estimates could also be strengthened by developing an extensive network of PM composition measurements alongside the CAAQMS network and by integrating modelling as a core tool for air quality management.

The inclusion of black carbon within climate strategies can enhance near-term climate benefits while amplifying existing mitigation efforts delivered through control measures targeting $PM_{2.5}$ reduction. Further, research could also assess the local climate benefits of reducing black carbon levels, such as changes in regional temperature, using climate model runs.

Future work should include more realistic and granular emission-reduction scenarios and assess their impacts on black carbon concentrations using the REACH modelling framework. With a detailed and granular emission inventory, a modelling framework such as REACH can provide valuable insights in prioritising emission mitigation scenarios. One such example is demonstrated in our previous report (CSTEP, 2025).

Another significant direction is the inclusion of understudied emission sources, such as wheat crop-residue during summer. To assess implementation feasibility, future work could estimate the costs of interventions through techno-economic assessment. This would enable policymakers to prioritise the most cost-effective strategies for maximising air quality, health, and climate co-benefits.

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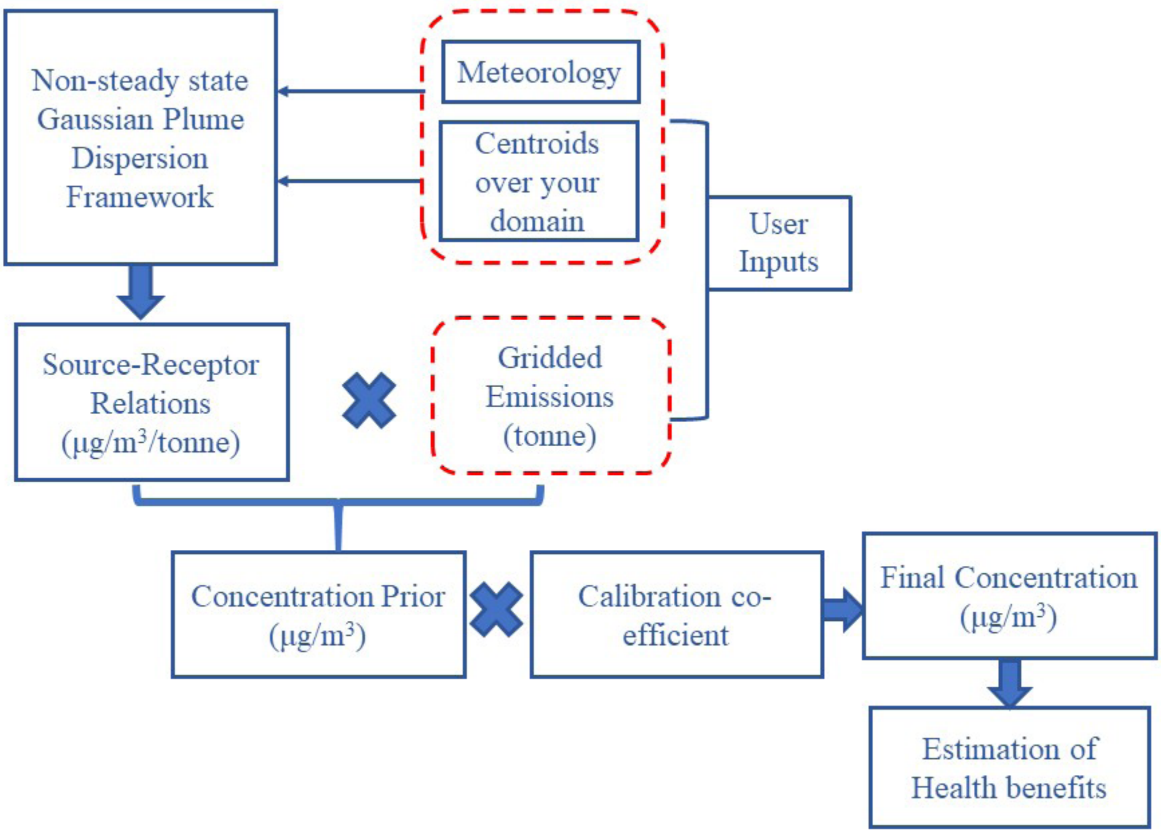
Annexures

Annexure 1: Model setup

The workflow of the REACH model is illustrated in Figure A1. The model operates independently of any chemical transport model, making it suitable for use in resource-constrained settings. It divides the simulation domain into a set of sources and receptors to construct a source–receptor matrix. Pollutant dispersion is characterised using Pasquill–Gifford stability classes, following Turner et al. (2020).

Figure A1: *Workflow diagram of the REACH model.*



The model incorporates a simplified chemical representation, as described below. Deposition processes during pollutant transport from source to receptor are represented within the modelling framework, with precursor deposition parameterised using species-specific atmospheric lifetimes. Secondary inorganic aerosol formation is estimated under the assumption of full neutralisation of sulphate and nitrate. Secondary organic aerosol (SOA) formation is represented using a simplified approach, in which volatile organic compound emissions are converted to SOA and subsequently adjusted using a correction factor.

Model bias is addressed through the application of a calibration coefficient, which adjusts simulated total $PM_{2.5}$ concentrations to reduce discrepancies with observations. The model is flexible with respect to input datasets and does not require a specific emissions inventory or meteorological product. In this analysis, meteorological inputs are derived from ERA5 reanalysis data.

Annexure 2: Absolute concentration of black carbon and $PM_{2.5}$ concentrations corresponding to baseline and emission-reduction scenarios

Scenario	BC concentration (µg/m³)	$PM_{2.5}$ concentration (µg/m³)
Baseline	2.55	63.10
Sc 1	2.54	63.09
Sc 2	2.54	63.09
Sc 3	2.51	63.06
Sc 4	2.49	63.04
Sc 5	2.48	63.03
Sc 6	2.41	62.96
Sc 7	2.38	62.93
Sc 8	2.23	62.78
Sc 9	1.95	62.50
Sc 10	1.6	62.16

Annexure 3: Definition of statistical metrics

Pearson correlation coefficient (r): It measures the strength and direction of the relationship between two datasets. Its value ranges from -1 to +1. Here, xi and yi represent individual values from the two datasets, while $\bar{x}$ and $\bar{y}$ represent their respective mean values. A high positive value indicates strong similarity, a value near zero indicates no correlation, and a negative score indicates an inverse relationship between the two datasets. The definition of r is provided below:

$$r = \frac{\sum(xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum(xi - \bar{x})^2}\sqrt{\sum(yi - \bar{y})^2}}$$

Coefficient of determination (R^2): It measures the ability of a model to explain observed variability. Here, xi represents the individual observed values, $\bar{x}$ represents the mean of the observed values, and yi represents the predicted model values for individual observations. The value of R^2 ranges from 0 to +1. A higher R^2 value indicates that the model explains a larger share of the observed variability. The definition of R^2 is provided below:

$$R^2 = 1 - \frac{\sum(xi - yi)^2}{\sum(xi - \bar{x})^2}$$

Root mean squared error (RMSE): It is the square root of the mean of the squared errors. Error is defined as the difference between model output and measurements. Here, xi represents the individual observed values and yi represents the predicted model values for individual observations. A lower RMSE indicates that the model predictions are closer to the measurements. The definition of RMSE is provided below:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i}(xi - yi)^2}$$

Mean normalised bias (MNB): MNB measures the average bias between predicted (*yi*) and observed values (xi) after normalising by the observed values (*xi*). Values closer to zero indicate lower model bias with respect to measurements. Positive values indicate model overprediction, while negative values indicate model underprediction. The definition of MNB is provided below:

$$MNB = \frac{1}{N}\sum_{i}\frac{yi-xi}{xi}$$

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Annexure 4: Policy mapping for black carbon and climate co-benefits

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
International	Paris Agreement (United Nations Framework Convention on Climate Change; UNFCCC)	2015	Global/ UNFCCC	Limit global warming to well below 2°C	Encourages inclusion of SLCPs and black carbon-rich sectors in national climate strategies and Nationally Determined Contributions (NDCs)	Reduces greenhouse gas (GHG) emissions, improves air quality and health, supports SDG 3 and 13
International	Kigali Amendment to the Montreal Protocol	2016	Global/ United Nations Environment Programme (UNEP)	Phase-down of hydrofluorocarbons (HFCs) globally	Targets HFCs (SLCPs) and promotes efficient cooling, which can reduce power-sector particulate matter (PM) and black carbon	Climate mitigation, energy savings, lower peak electricity demand
International	Climate and Clean Air Coalition	2012–	Voluntary partnership	Accelerate action on SLCPs	Focuses on methane, black carbon, HFCs, and tropospheric ozone through sectoral initiatives	Rapid health benefits, crop-yield protection, regional climate gains
International	World Health Organisation (WHO) Air Quality Guidelines	2021	WHO	Provide health-based air-quality benchmarks	Tightens guideline values for $PM_{2.5}$ and PM_{10}, where black carbon is a major fraction in many settings	Large potential reductions in premature mortality and non-communicable diseases burden

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
National (India)	Air (Prevention and Control of Pollution) Act	1981/1987	Ministry of Environment, Forest and Climate Change (MoEFCC), Central Pollution Control Board (CPCB), State Pollution Control Boards (SPCBs)	Provide legal basis to prevent and control air pollution	Enables regulation of particulate emissions and precursors across sectors, indirectly reducing black carbon	Foundational for environmental governance, enabling enforcement and penalties
National	National Ambient Air Quality Standards (NAAQS)	2009	CPCB	Set permissible limits for major air pollutants	$PM_{2.5}$ and PM_{10} standards drive measures that reduce black carbon and other PM components	Guides health-based risk management and identification of non-attainment cities
National	National Clean Air Programme (NCAP)	2019–	MoEFCC	Achieve a 20%–30% reduction in PM concentrations in selected cities, subsequently revised to 40%	Targets key black carbon-rich sources such as transport, industry, waste burning and household fuels	Health improvement, productivity gains, climate co-benefits through PM and SLCP reductions
National	National Air Quality Index	2015–	CPCB	Communicate air-quality status to the public	Uses $PM_{2.5}$, PM_{10} and key gases to trigger awareness and graded responses that curb black carbon	Supports informed public behaviour and timely regulatory action

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
National	Graded Response Action Plan – Delhi-NCR	2017, rev. 2023	Commission for Air Quality Management in National Capital Region and Adjoining Areas, CPCB, state governments	Implement graded measures during high-pollution episodes	Imposes temporary curbs on high black carbon sources such as construction, industries, diesel generator sets, and vehicles	Rapid short-term exposure reduction and visibility improvement
National	Waste Management Rules: solid, plastic, hazardous, biomedical, construction and demolition, and e-waste	2016–	MoEFCC, urban local bodies (ULBs)	Modernise and regulate waste management systems	Discourages or bans open waste burning, a growing source of black carbon and organic carbon emissions	Supports cleaner cities, reduced toxic emissions, and lower SLCP and GHG releases
National	Bharat Stage IV/ VI Vehicle & Fuel Standards	2017/2020	Ministry of Roads, Transport and Highways, Ministry of Petroleum and Natural Gas (MoPNG)	Tighten emission and fuel quality standards for vehicles	Significantly cuts tailpipe $PM_{2.5}$ and black carbon, especially from diesel vehicles	Urban air-quality gains, fewer respiratory and cardiovascular diseases

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
National	National Electric Mobility Mission Plan/FAME	2013–	Ministry of Heavy Industries, NITI Aayog	Promote electric vehicle (EV) adoption and charging infrastructure.	Replaces conventional vehicles, reducing urban black carbon and NO_x where electricity is relatively cleaner	Reduced noise, climate benefits via CO_2 and SLCP reduction
National	Pradhan Mantri Ujjwala Yojana	2016–	MoPNG	Provide LPG connections to low-income households	Reduces household black carbon emissions from biomass and coal cookstoves	Major health benefits for women and children, time savings, climate co-benefits
National	Pradhan Mantri Sahaj Bijli Har Ghar Yojana (Saubhagya) for rural electrification	2017–	Ministry of Power, state governments	Achieve universal household electrification	Enables households to shift from kerosene lamps, lowering black carbon and CO_2 from lighting	Improved living conditions, education outcomes, reduced indoor air pollution
National	Brick kiln zig-zag conversion norms	~2017–	SPCBs, MoEFCC	Improve energy efficiency and reduce emissions in brick kilns	Lowers black carbon-rich emissions per unit of brick produced	Better local air quality, fuel savings and reduced climate impact

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
State – Punjab	Punjab Action Plan on Air Quality/NCAP City Plans	2019–	Punjab Pollution Control Board (PPCB), ULBs	Achieve National Ambient Air Quality Standards in identified non-attainment cities	Combines transport, industry, construction, and waste measures that together contribute to reducing black carbon and $PM_{2.5}$ emissions	City-level health benefits and improved compliance with national standards
State – Punjab	State Action Plan on Climate Change (SAPCC)	Latest revision year	Dept of Science, Technology & Environment	Integrate climate concerns into sectoral policies	Addresses agriculture, energy, transport and waste—sectors rich in SLCP and black carbon emissions	Synergies across resilience, mitigation, and air-quality improvement
State – Punjab	Crop Residue Management schemes	2018–	Dept of Agriculture, Ministry of Agriculture and Farmers' Welfare	Reduce stubble burning through incentives and machinery	Directly tackles a major seasonal black carbon and organic carbon source in Punjab and the Indo-Gangetic Plain (IGP)	Cleaner air, improved soil health and visibility, reduced regional haze events
State – Punjab	Promotion of happy seeders and mechanisation	2017–	Dept of Agriculture, Indian Council of Agricultural Research, states	Facilitate in-situ residue management and conservation agriculture	Avoids open burning by allowing sowing into standing stubble, lowering black carbon emissions	Enhances soil moisture, reduces labour demand, and operational costs over time
State – Punjab	City-level bans on open waste burning	2016–	ULBs, PPCB	Eliminate visible waste burning within city limits	Reduces black carbon, organic carbon and toxic pollutants from informal burning practices	Local health gains, improved urban environment, climate co-benefits

Level	Policy	Year	Agency	Main objective	Relevance to black carbon and short-lived climate pollutants (SLCPs)	Key co-benefits: Air quality, health, climate, Sustainable Development Goals (SDGs)
Other IGP States	State Air Quality Action Plans under NCAP	2019–	SPCBs, ULBs	Reduce PM levels in non-attainment cities across IGP states	Prioritise black carbon-rich sources like transport, brick kilns, industry, and waste and biomass burning	Regional health improvement and economic productivity gains
IGP States	State SAPCCs (Haryana, UP, Bihar, Rajasthan, etc.)	Various	State environment and climate departments	Mainstream climate action in state development planning	Recognise SLCP-intensive sectors and potential for integrated black carbon and GHG mitigation	Multiple SDG co-benefits in agriculture, energy, and urban development
IGP States	Crop residue management and burning bans	2015–	Agriculture departments, SPCBs	Control agricultural burning in IGP states	Aim to reduce farm-fire-driven black carbon and $PM_{2.5}$ peaks	Better air quality, reduced smog episodes, safer road and air transport
IGP States	Urban transport policies: CNG/EV promotion, bus rapid transit/ metro	Various	State transport depts, ULBs	Improve and clean urban mobility	Lower black carbon and NO_x emissions due to shifting away from diesel and private vehicles	Less congestion, noise, and greenhouse-gas emissions
IGP States	State waste management and ‘no-burn’ by-laws	2016–	ULBs	Strengthen municipal solid-waste systems and prevent burning	Target black carbon-rich emissions from informal dumpsite and roadside burning	Cleaner neighbourhoods, reduced disease vectors, and climate co-benefits

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Sanjukta Ghosh is a Senior Analyst at CSTEP. She is responsible for the REACH model setup and for assessing black carbon emission mitigation scenarios using the model. She also analysed the associated air quality, health, and climate co-benefits for those scenarios over the Indo-Gangetic Plain. She played a leading role in analysing the results and writing the report.

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