# PRIMER ON NON-CARBON DIOXIDE POLLUTANTS IN INDIA

Cont

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# EXECUTIVE SUMMARY

India's efforts to address climate change have often centered on carbon dioxide ($CO_2$), but with growing evidence of the substantial impact of short-lived climate pollutants (SLCPs), this focus is sharpening. SLCPs, including black carbon, methane, tropospheric ozone, hydrofluorocarbons (HFCs), and nitrous oxide ($N_2O$), are potent contributors to climate change, accelerating global warming with far-reaching implications for health, agriculture, and the environment. Despite their relatively short atmospheric lifetimes compared to $CO_2$, SLCPs have intense warming effects, making their reduction a crucial step toward meeting India's climate goals. This Primer by IGSD India program provides a comprehensive overview of SLCPs in India, outlining sources, impacts, and potential mitigation strategies.

## Importance of SLCPs for India's Climate Goals

SLCPs contribute up to 45% of current global warming, with black carbon, methane, and HFCs being among the most significant contributors. Their short atmospheric lifespan—ranging from a few days to around 15 years—means that reducing SLCPs can yield immediate climate and health benefits. Mitigating these pollutants can slow down the warming rate, provide near-term relief from air pollution, and help India adapt more effectively to climate impacts. For instance, the reduction of black carbon and methane emissions alone could cut the current rate of global warming by half and avert approximately 0.6°C of warming by 2050, aiding India in achieving its climate targets under the Paris Agreement.

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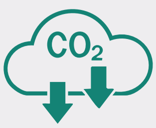
## Sector-Specific Contributions and Challenges

India's SLCP emissions originate primarily from the energy, agricultural, waste, and industrial sectors, each presenting unique challenges for mitigation.




**Black Carbon:** Predominantly emitted from biomass burning and fossil fuel combustion, black carbon contributes to both warming and poor air quality. The Indo-Gangetic Plain, with its high population density and widespread reliance on biomass fuels for cooking and heating, is a significant hotspot. In addition to impacting local air quality, black carbon also accelerates the melting of Himalayan glaciers, affecting water resources for millions.


**Methane:** Agriculture, particularly livestock and rice paddies, is a significant methane emitter in India. The waste sector, through landfills and wastewater treatment, also contributes substantially. Methane's potency as a greenhouse gas—28 times more warming than $CO_2$ over a 100-year period—means its mitigation is key to managing near-term climate risks. However, efforts are hindered by data limitations, particularly in agriculture and waste management, making it difficult to gauge the full scale of emissions and assess the effectiveness of mitigation policies.


**Tropospheric Ozone:** Formed through chemical reactions involving methane, nitrogen oxides, and volatile organic compounds, ozone has a dual impact as a climate forcer and an air pollutant. High ozone levels harm crop yields, particularly in the Indo-Gangetic Plain, leading to reduced agricultural productivity.


**Hydrofluorocarbons (HFCs):** Widely used in refrigeration and air conditioning, HFCs have a warming potential thousands of times greater than $CO_2$. While alternatives exist, they require policy support and financial incentives for widespread adoption.

## The Data Challenge and Need for Robust Monitoring

A critical issue in SLCP management is the lack of comprehensive, high-resolution data on emissions. India's existing monitoring systems often fail to capture detailed data on sources such as smallholder farms, dispersed waste sites, and informal industrial sectors, limiting the effectiveness of policy and regulatory measures. Additionally, where data exist, they may be outdated or lack the spatial granularity needed to inform targeted interventions. For instance, the latest methane emissions inventory dates to 2016, and black carbon inventories are sparse and not government-backed.

his data gap underscores the need for enhanced monitoring infrastructure. IGSD's work to develop India's first sub-national SLCP inventories, with a 12x12 km grid resolution, marks a crucial step forward, allowing for more precise emissions mapping. Such data improvements will enable India to design tailored policies, improve compliance monitoring, and measure progress accurately—essential for driving impactful SLCP reduction efforts across states and sectors.

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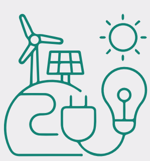
## Potential Solutions and Mitigation Strategies

Several mitigation strategies can help India address SLCP emissions effectively, contributing to both climate and development goals:

**Agriculture:** Methane emissions from rice paddies and livestock can be reduced by implementing water-saving practices such as Alternate Wetting and Drying (AWD) in rice fields and by using feed additives to reduce enteric fermentation in livestock. Sustainable crop management techniques and carbon credits for biogas production offer further opportunities to incentivize farmers and reduce methane emissions sustainably.

**Waste Management:** Improved waste segregation, biogas generation from organic waste, and landfill gas capture are promising methods to reduce methane emissions. Bioremediation of legacy waste is also critical for managing methane emissions from existing dumpsites.



**Energy Sector:** Reducing black carbon from energy production involves transitioning to cleaner fuels and adopting more efficient technologies. Policies that encourage the use of LPG for cooking and electric or low-emission transport can mitigate black carbon emissions significantly. For methane, pre-mining drainage and improved ventilation in coal mines, as well as enhanced monitoring of oil and gas infrastructure, can help capture fugitive emissions.

**Industrial Sector:** Adopting market-based mechanisms, such as emissions trading systems specifically for black carbon and methane, can help regulate emissions while providing economic incentives for industries to adopt cleaner technologies.

## Policy Recommendations and the Path Forward

To advance SLCP reduction, India's approach must be multi-faceted, integrating policy, technology, and community engagement. Key recommendations include:

01

**Strengthening Data Infrastructure:** Investment in advanced monitoring systems and regional emissions inventories will bridge current data gaps, allowing policymakers to make informed decisions. Establishing comprehensive and regularly updated SLCP inventories at both national and sub-national levels will be critical.

02

**Encouraging Cross-Sectoral Coordination:** SLCP mitigation requires integrated action across sectors like agriculture, waste, and energy. Developing policies that incentivize collaboration, such as linking agricultural biogas projects with waste management systems, can enhance impact and drive cost efficiencies.

03

**Supporting Technological and Financial Innovation:** Providing financial incentives for cleaner technologies, such as HFC-free cooling appliances and methane capture systems, will support the adoption of low-emission technologies. Additionally, expanding access to carbon markets can encourage investment in SLCP reduction projects, generating revenue for sustainable development initiatives.

04

**Building Public Awareness and Engagement:** Effective SLCP management involves raising awareness among key stakeholders, including farmers, industrial operators, and the public. Educational campaigns on the health and environmental impacts of SLCPs, coupled with incentives for low-emission practices, can foster community support for mitigation efforts.

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India's commitment to reducing SLCPs is integral to its climate action strategy and offers an avenue for achieving rapid, measurable reductions in warming. Tackling SLCPs not only benefits the climate but also addresses pressing local issues such as air pollution and public health. As India prepares for COP29, it is well-positioned to lead the Global South in SLCP mitigation, demonstrating that climate resilience and economic growth can coexist. Enhanced data, strategic policy, and cross-sectoral collaboration will be instrumental in translating India's SLCP goals into tangible results, paving the way for a sustainable, low-emission future.

# INTRODUCTION

## Global Landscape and India

Six Intergovernmental Panel on Climate Change (IPCC) reports, countless scientific evidence, and 28 Conference of Parties (CoP) later, the dangers of a warming planet continue to intensify. In 2023, both global and North Atlantic sea-surface temperatures majorly exceeded their averages, since 1991, for most of the year.[1] However, while climate change continues to be a global emergency, its impacts are seen as disproportionate for Global South nations. South Asia is very susceptible to extreme weather events, including river flooding, sea-level rise, and extreme temperatures. These in turn are serious risk factors for food supplies, livestock, land, and crops in the region. In India, for instance, farms are negatively impacted and destroyed every year by severe heatwaves and snowstorms caused by climate change. Very conservative estimates suggest that South Asian economies including India have a high chance of witnessing a 1.8% reduction of the national gross domestic product by 2050, which could rise to 8.8% by 2100. If the self-amplifying feedback loops push the planet past the 5 irreversible tipping points that are anticipated at 1.5C, the economic impact will be an order of magnitude that is unfathomable.[2]

To prevent the catastrophic impacts of climate change on humanity, the IPCC has highlighted the urgent need for substantial reductions in greenhouse gas emissions by 2035. This aligns with the Paris Agreement, which seeks to keep global temperature rise well below 2°C, with efforts to limit the increase to 1.5°C.

Given the limited time available and the increasing frequency of extreme weather events worldwide, it is crucial to develop an immediate action plan. While decarbonization is a long-term goal, there is now an urgent need for a broader approach to greenhouse gases, focusing on rapid, short-term emissions reductions. Though carbon dioxide ($CO_2$) is a major greenhouse gas, we must also enhance our understanding of the role of non-$CO_2$ emissions—specifically Short-lived Climate Pollutants (SLCPs)—in global warming and their significance for local adaptation strategies.

## What are SLCPs and Why They Matter

Short-lived climate pollutants (SLCPs) are potent climate forcers that, despite their relatively brief atmospheric lifetime compared to carbon dioxide ($CO_2$), possess a significantly higher capacity to induce atmospheric warming. The primary SLCPs—black carbon, methane, tropospheric ozone, and hydrofluorocarbons (HFCs)—are the most significant contributors to anthropogenic global warming after $CO_2$, accounting for up to 45% of the current global warming. Without targeted mitigation efforts, the contribution of SLCPs to human-induced warming could increase to nearly 50% in the coming decades.[3]

SLCPs remain in the atmosphere for a relatively short period, from a few days to a couple of decades, which essentially means that strategies that target these pollutants can achieve more effective mitigation of global warming in the immediate term. The IPCC Sixth Assessment Report underscores this importance of mitigating SLCPs to achieve short-term climate goals as well as to address a sizeable part of the larger mitigation gap.[4]

Further, IGSD research clarifies that reduction of "non-$CO_2$ climate pollutants" especially SLCPs, can help to:

- Avoid four times more global warming by 2050 than cutting $CO_2$ only
- Decrease the rate of global warming by half
- Reduce projected warming in the Arctic by two-thirds

SLCP mitigation also holds ramifications for a country like India which contends with poor air quality. Thus, it becomes essential to unpack the specific relationship between air pollution and these SLCPs. For instance, black carbon and tropospheric ozone are potent local air pollutants. Black carbon is a powerful climate-warming particle that is a component of fine particulate matter, specifically PM2.5. Methane is related to tropospheric ozone, which is an air pollutant responsible for millions of premature deaths, and billions of dollars' worth of crop losses annually. The IPCC had noted in its most recent AR6 Synthesis Report that "strong, rapid and sustained reductions in methane emissions can limit near-term warming and improve air quality..." Further, according to India's third Biennial Update Report to the UNFCCC, methane accounted for 19.5 million tonnes or 14.43% of India's total GHG emissions in 2016.

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## SLCPs Featured in the India Primer

This primer seeks to foreground the primary SLCPs, outline the impacts they have, and offer potential solutions that can be deployed at scale in the future. The SLCPs the primer shall delve into include:

| SLCPs | Global Warming Potential | Average atmospheric life |
|---|---|---|
| Methane | 28 times that of $CO_2$ | 12 years |
| Black Carbon | 1,055–2,240 times that of $CO_2$ | 12 days |
| Tropospheric Ozone | | Few hours to weeks |
| Hydrofluorocarbons | 12,000 times that of $CO_2$ | 15 years |

1

**Methane (CH4):** A super-potent planet-warming gas, a kilogram of CH4 emissions has over 80 times the global warming power of a kilogram of carbon dioxide ($CO_2$) emissions over 20 years. About 45% of today's net global warming is driven by methane emissions from human activities.[5]

2

**Black Carbon (BC):** BC is a strong climate-forcing aerosol with an atmospheric lifetime of only a few days or weeks and is the second-leading cause of global warming. It is the light-absorbing component of PM and is mainly emitted from the incomplete combustion of fossil fuels and biomass-based fuels. At the ground level, BC tends to warm the atmosphere directly through the absorption of solar radiation which it then emits as heat. BC can also affect the microphysical properties of cloud formation and thus disturb precipitation patterns. It is also a potent air pollutant leading to serious health impacts.

3

**Tropospheric Ozone (O3):** Ozone as a reactive gas is a key absorbent of harmful ultraviolet radiation in Earth's stratosphere. However, at the lower level (tropospheric level), ozone is a substantial air pollutant with diverse impacts on human health and crop production.

4

**Hydrofluorocarbons (HFCs):** HFCs are synthetic gases used primarily as refrigerants, solvents, and in foam production. These have a warming effect that is hundreds to thousands of times more powerful than $CO_2$. Emissions of HFCs mainly occur from leakages during the use and disposal of products containing HFCs.

5

**Nitrous Oxide ($N_2O$):** $N_2O$, also commonly known as laughing gas, is a long-lived greenhouse gas with an average atmosphere life of 273 years. With rising emissions, nitrous oxide is projected to be the second highest pollutant which will be a key driver to global warming after $CH_4$.

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[6] Bond, T.C., et al. (2013). *Bounding the role of black carbon in the climate system: A scientific assessment*. Journal of Geophysical Research: Atmospheres; 118(11): 5380-5552.

[7] Szopa, S., & Naik, V. *IPCC: Sixth Assessment Report*, 2023 Ibid.

# BLACK CARBON

## Introduction

Often characterized as one of the most potent pollutants[1], black carbon has one of the shortest atmospheric lifespans of about two weeks on average.[i] Black Carbon is a Short-Lived Climate Pollutant (SLCP) which absorbs approximately one million times more solar energy than $CO_2$ per unit mass (Bond and Sun, 2005). Research studies point to black carbon being the third-largest contributor to the positive radiative forcing[2] that causes global rise in temperature.

Black carbon is formed as a result of incomplete combustion of carbon-based fuels when oxygen is insufficient for complete combustion. Colloquially referred to as soot, it is a distinct carbonaceous material. It is routinely emitted along with Organic Carbon (OC) compounds and sulphates, which have a cooling effect through direct light scattering and interactions with clouds (Ramanathan and Carmichael, 2008). Apart from being a strong absorber of visible light, Black Carbon aerosols are initially hydroscopic (water-repellent), with a tendency to become hygroscopic (water-attracting) over time.[3][ii] This increases their tendency to form cloud condensation nuclei (CCN) which helps in cloud formation.

Black carbon emissions are known to greatly vary spatially, and temporally, localizing its impacts on health and environment.

India is the second-largest emitter of black carbon in the world after China,[iii] with most of its emissions resulting from the burning of inefficient domestic fuels, followed by emissions from industries.[iv] The Indo-Gangetic Plain[4] (IGP) is a hotspot for black carbon, with its concentrations amplified during winter due to increased biomass burning.

### Indo-Gangetic Plain (IGP)

**According to a study conducted in 2011, the state of Uttar Pradesh, with annual emissions of 140 gigagram (Gg) was the largest emitter of Black Carbon, followed by West Bengal (58 Gg), Bihar (48 Gg), Punjab (34 Gg), and Haryana (27 Gg). Located within the IGP region, this densely populated state witnesses the usage of high-emission fuels for heating and cooking in the residential sector. Further, the presence of industries such as thermal power plants and sugar and brick production units aggravate the problem of pollution.[v] The region also receives pollution from aerosols transported over long distances from Pakistan, Afghanistan, and West Asia.[vi]**

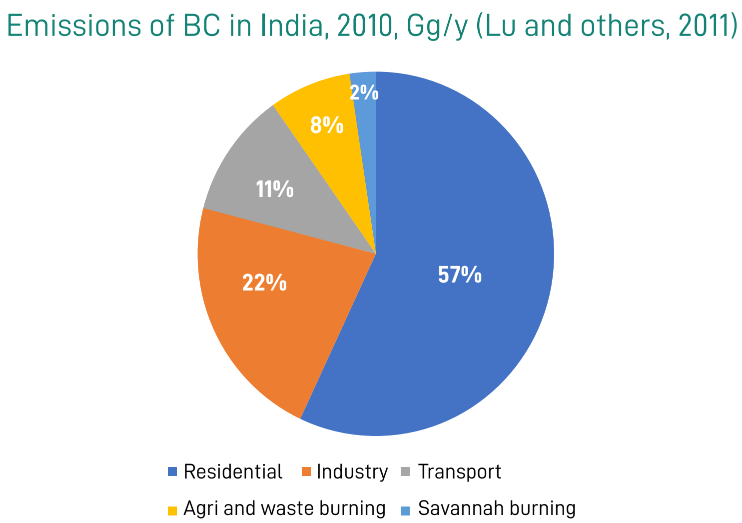
Owing to its short lifespan, BC mitigation can generate immediate results in reducing climate forcing.[5] Research also suggests that reduction in BC emissions could potentially reduce premature mortality to the extent of four to 12 million avoided deaths between 2015 and 2030.[vii] In India, 300 million people reside in the IGP. Among them, 60 million live in BC hotspots and, consequently, face heightened risk of cardiovascular diseases (CVD).[viii] Research has estimated that BC is associated with 6.8% increased mortality risk during winter.[ix]

# Issues: BC Emission Sources & Its Impacts

Sources of BC emissions are broadly classified into fossil fuel-based sources ($BC_{ff}$) and emissions attributable to biomass burning ($BC_{bb}$). In India, unlike rest of the world, a majority of BC emissions come from biomass burning. Within urban conglomerations, fossil fuels are the primary emitters of BC emissions. BC emitted from biomass burning have different characteristics than those emitted from fossil fuels. Emissions from biomass burning have a higher OC to BC ratio than emissions from fossil fuels. OC has a relative cooling effect on the atmosphere.[x]

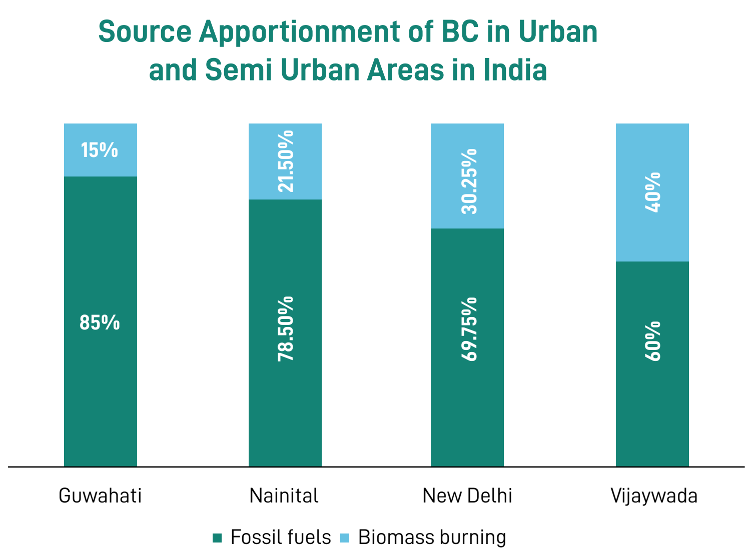
## Source Apportionment in India

In a research study conducted by Lu Z and others, biofuel was observed to be the dominant emitter of black carbon (45%–52%), followed by coal (22%–29%) and oil (14%–17%). The distribution of BC emissions among different sectors was relatively stable during the study period of 1996–2010[xi]. The residential sector was the highest emitter, at about 57%, followed by the industry sector at 22%, transportation at 11%, agricultural and waste burning contributing 8%, and savanna burning responsible for 2% of black carbon emissions.




## Source Apportionment in Urban Areas

In all studies conducted by different researchers in select cities, fossil fuels are the major emitters of black carbon. Srinagar Nainital, and Guwahati located in north, central, and eastern Himalayas have fossil fuels as the major sources of BC emissions. Compared to other cities, Delhi has a higher proportion of emissions from biomass burning, as can be seen in the graph. In Vijayawada, a semi-urban settlement, the proportion of emissions from biomass burning is higher, at 40%, pointing to the fact that in rural areas, biomass may be the main source of black carbon emissions.




A cause for concern is the fact that BC emission levels in remote locations such as hill stations in Himalayas and islands in India, are 2-10 times higher than in similar locations worldwide.[xii]

## Impacts

**1. Global Warming**

Black carbon is one of the most powerful climate-warming pollutants. Its radiative forcing value, which measures its heat-trapping effect, averages +1.1 W/$m^2$ but can range from +0.17 to +2.1 W/$m^2$.[xiii] Studies show that the warming effect of black carbon is nearly twice that of all other greenhouse gases combined[xiv]. According to the IPCC, black carbon is the third largest contributor to global warming. However, estimates of its impact on warming vary because different studies use different models, and the effect of black carbon tends to be highly localized, making it difficult to calculate accurately.

**2. Impact on Himalayan Glaciers**

As strong absorbers of incoming infrared rays, BC aerosols are known to increase the pace of glacial melt in Himalayas. The deposition of black carbon aerosols on glaciers reduces the albedo (reflectivity) of glacial ice, thereby increasing the proportion of sunlight absorbed by it.[xv] This increased absorption of sunrays accelerates melting and sets in a vicious cycle.[xvi] The Himalayas have become vulnerable to black carbon emissions in recent years. Studies have estimated that around 1% of glacial melt in the Himalayas can be attributed to aerosols.[xvii] This poses a severe threat to food security in the region, with the Himalayan rivers providing access to water to over 25% of the global population.

Black carbon emissions are shifting rainfall patterns over India. BC aerosols impact the heating rates of the atmosphere which in turn impacts cloud formation and precipitation. However, its impact cannot be generalised in Manichean terms as the relationship of BC can either increase or decrease rainfall based on cloud formation, which is dependent on the altitude where BC aerosols are found.[xviii] In the Indian subcontinent, some modelling estimates predict a weakening of the Indian monsoons due to reducing temperature gradient between landmass and sea[xix]. Other research suggests that increasing BC emissions can lead to increased monsoon precipitation over the Indo-Gangetic plains and reduced rainfall over peninsular India.[xx] Therefore, the relationship between black carbon emissions and rainfall patterns in India are complicated to unravel; however, it is certain that monsoon rainfall would become more uncertain.

**3. Potential Impact on Agricultural Productivity**

In India, a major contributor of BC emissions is the agriculture sector. But it also, ironically, stands to be an affected sector because of this very reason. According to IPCC, BC emissions have a direct impact on agricultural productivity.[xxi] BC emissions, along with air pollutants including ozone, could have reduced yield of wheat by 36% between 1980 and 2010 in the IGP region.[xxii]

**4. Health Impacts**

PM2.5 emissions, of which black carbon forms an important component, is associated with negative health impacts such as respiratory illnesses. Black carbon is one of the most toxic components of PM2.5 emissions. Studies have shown that it causes inflammation in pulmonary tissues and increases morbidity risks.[xxiii] BC emissions are also linked with increased cardiovascular mortality. BC aerosols also tend to absorb and adsorb other toxic components such as Polycyclic Aromatic Hydrocarbons (PAHs)[xxiv], a known carcinogen. These adverse health impacts are associated with occupational health diseases among women who engage in cooking with biomass who come from vulnerable sections of society in India.

## Impacts

*National Initiatives*

- **The Air (Prevention and Control of Pollution)** Act was enacted in 1981 and amended in 1987 to provide for the prevention, control and abatement of air pollution in India. It is the primary law governing air and noise pollution in the country. The act empowers the Central Pollution Control Board to set air quality standards, monitor the standards and advise the central government on issues related to air quality.
- The Central Pollution Control Board has laid out the **National Ambient Air Quality Standards** with 12 pollutants which includes five gaseous pollutants ($SO_2$, $NO_2$, $O_3$, CO and $NH_3$), two dust-related parameters (PM10 and PM2.5, three metals (Lead, Nickel and Arsenic) and two organic pollutants (Benzene and B(a)P – particulate phase). Internationally, the World Health Organization considers a select set of pollution indicators to ensure the monitoring of air pollution. This is because the quantification of all air pollutants has not been feasible on a global scale. It focuses on four major air pollutants - particulate matter, both PM2.5 and PM10; along with gaseous pollutants such as nitrogen dioxide, sulphur dioxide, and ozone.

*Actions taken by the Central Pollution Control Board include:*

- **National Air Quality Index (AQI)** was launched in 2015. Information is being disseminated to the public through daily air quality bulletins. AQI is monitored along with other parameters and is published on the website in the form of AQI bulletins after analyses. The links for the same are also made available to CAQM for consideration, for helping them decide on urgent actions for control of pollution in Delhi-NCR.
- **Ambient Air Quality Network:** The country has a network of 1447 ambient air quality monitoring stations (516 continuous and 931 manual) covering 516 cities in 28 states and 7 UTs. It consists of 804 operating stations covering 344 cities/towns in 28 states and 6 Union Territories of the country.
- **A Central Control Room** is operated by Central Pollution Control Board wherein, hour to hour tracking of various information such as PM concentrations, Live Air Quality Data of Monitoring stations, Live Air Quality Index is available. Further, the Air Quality Forecast is also available for Delhi-NCR.

*Other actions taken by the government include:*

- **National Clean Air Programme (NCAP):** To control air pollution at a national scale, the Government of India launched the National Clean Air Programme in 2019, with the target to reduce PM2.5 and PM10 concentration levels by 20-30% by 2024. The NCAP aims to strictly implement air pollution mitigation measures to reduce air pollution concentration, strengthen the air quality monitoring network, ensure data to support air quality management, and strengthen awareness and capacity building. The target has been revised to achieve reduction in PM10 levels up to 40% or achievement of national standards (60 µg/m3) by 2025-26.

  To prioritize air pollution mitigation, the CPCB has identified 131 cities (non-attainment polluted cities and Million Plus cities) where the prescribed The National Ambient Air Quality Standards (NAAQS) was not being met for a long time. City-specific Clean Air Action Plans have been prepared and rolled out for implementation in these non-attainment cities to improve the air quality. These plans have short-, medium-, and long-term actions for city-specific air polluting sources like Soil & Road Dust, Vehicles, Domestic Fuel, MSW Burning, Construction Material and Industries along with the responsible agencies. Urban local bodies are the primary stakeholders responsible for the implementation of these plans and provide performance-based financial support to these 131 cities for the implementation of activities listed under the City Action Plan.

### Graded Response Action Plan (GRAP)

The Graded Response Action Plan (GRAP) is a framework designed in 2017 to combat air pollution in the Delhi-NCR region. It was introduced as an emergency response mechanism, and its implementation is triggered when the AQI reaches "poor" levels. In 2023, the Commission for Air Quality Management in NCR & Adjoining Areas (CAQM) revised the existing Graded Response Action Plan (GRAP) to combat air pollution in the region. The revised GRAP contains targeted actions that need to be taken by the agencies responsible/ implementing agencies when AQI (Air Quality Index) of Delhi goes beyond a certain threshold.

### Sector-Specific Initiatives

Focusing on pollution from waste, five waste management rules on solid waste, hazardous waste, plastic waste, biomedical waste, and e-waste have been revised; and the rules pertaining to construction and demolition waste as a major source of dust pollution were newly notified during 2016. Further, a ban was imposed on the burning of leaves, biomass, and MSW. There are other measures which were taken by the government for improvements in energy efficiency and air pollution control in India, some of which are cited below:

- Advanced vehicle emission and fuel quality standards– BS IV from 2017 and BS-VI from 2020.
- Plan to introduce a voluntary fleet modernization and an old-vehicle scrappage programme in India.
- Introducing a National Electric Mobility Mission Plan 2020.
- Introducing gas as an automotive fuel in many cities.
- Introduction and enhancement of the metro-rail and bus-based public transport systems in selected cities.
- Pradhan Mantri Ujjwala Yojana or scheme to accelerate LPG penetration programme for cooking in households.
- Electrification to reduce kerosene consumption for lighting.
- Notifying new stringent standards for diesel generator sets for standby power generation.
- Conversion of low-efficient brick firing technology to low-polluting zig zag technology in the NCR.
- Complete ban on stubble and refuse burning

## Challenges

### Measurement of Black Carbon Emissions

Measuring BC emissions using existing instruments are challenging in remote areas such as Himalayas. Further, due to lack of any long-term estimates of BC emissions, most studies model the emissions of black carbon. This leads to great variations in emission estimates by different studies as a result of multiple methods applied. Moreover, there is no widely accepted standard measurement practice for measuring and estimating black carbon emissions.

## Disproportionate Impact on Vulnerable Section of Society

Black carbon has a disproportionate impact on the poor and vulnerable sections of society. One of the primary causes of air pollution is cooking with biomass, which is still practised in India despite the Pradhan Mantri Ujjwala Yojana (PMUY) which provides subsidy for purchasing clean cooking fuel. Researchers have remarked that the Indian poor face a double burden of air pollution - indoor pollution and high ambient air pollution levels. Studies also conclude that low-income households face the brunt of all pollution sources. They suffer indoor air pollution from their own cooking; and they also face a disproportionate share of mortality risks from ambient air pollution including from electricity generation and other industries to which their consumption contributes relatively little.

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# Potential Solutions & Way Ahead

## Bridging the Data Gap

The existing monitoring gap needs cost-effective alternatives. Therefore, traditional monitoring measuring instruments such as aethalometers can be combined with the use of low-cost monitoring devices such as microAeths. They are portable and can monitor real-time emissions of black carbon at the point source such as waste burning sites and highways. This hybrid approach can be used to bridge the existing data gaps for monitoring and measuring black carbon emissions.

## Market Mechanisms

Market mechanisms such as an emission trading system can be a potential solution that ensures targeted reduction in black carbon emissions. Surat city became the first government in the world to introduce an emissions trading system (ETS) for particulate matter. The Surat Clean Air Market has seen a 24% drop in verified emissions reductions. Overall, a total of 317,468 kg of PM2.5 were avoided from being emitted by the industries of Surat. A similar market mechanism can be introduced to reduce black carbon emissions. Furthermore, since black carbon is a component of particulate matter, an ETS for PM2.5 also has the positive co-benefit of reducing black carbon emissions, that can be calculated using emission factors and energy utilised by the industry.

## Increasing the Involvement of Local Governments

Since BC emission sources and impacts are highly local, local governments should initiate specific policies and targeted programmes aimed at reducing BC emissions effectively. In Delhi, Supreme Court directives were responsible for changes in local policies which reduced its air pollution. The conversion of all public transport fleet into CNG successfully reduced PM2.5 emissions per vehicle by almost 90%. Other measures such as imposing an additional charge for trucks and diesel vehicles, imposing new restrictions on truck movement in the city, and phasing out old diesel vehicles have reduced their registrations by 28% between 2014 and 2022.[6]

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[2] Radiative Forcing is the change in the energy balance of the earth system due to some imposed disturbance

[3] https://www.pnas.org/doi/pdf/10.1073/pnas.0909605107

[4] The Indo-Gangetic Plain is a large and fertile region in northern and eastern India, extending into parts of Pakistan, Nepal, and Bangladesh. In the Indian context, it is bounded by the Himalayas to the north and the Deccan Plateau to the south, covering states like Punjab, Haryana, Uttar Pradesh, Bihar, West Bengal, and parts of Rajasthan and Madhya Pradesh.

[5] Rana A, Jia S & Sarkar S. (2019) Black carbon aerosol in India: A comprehensive review of current status and future prospects, ATMOS.RES. Volume 218, ("India is currently the second-largest emitter of black carbon (BC) in the world, with emissions projected to rise steadily in the coming decades.")

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# METHANE

## Introduction: Methane as an SLCP & Its Significance to India's Climate

Methane ($CH_4$) is a major organic trace gas with significant atmospheric impact.[1] It is produced naturally in wetlands and marine sediments, as well as through human activities like livestock farming, rice cultivation, landfills, and energy production. Although it is a primary component of natural gas, $CH_4$ has a global warming potential which is 28 times greater than Carbon Dioxide ($CO_2$) over 100 years.[2] It is a key contributor to climate change, especially in India, where agriculture, landfills, and energy production drive emissions. Although it is emitted in smaller quantities than $CO_2$, methane's higher warming potential makes its reduction critical for limiting global temperature rise. Beyond its climatic effects, methane also contributes to air pollution and ground-level ozone formation, impacting air quality and human health.[3]

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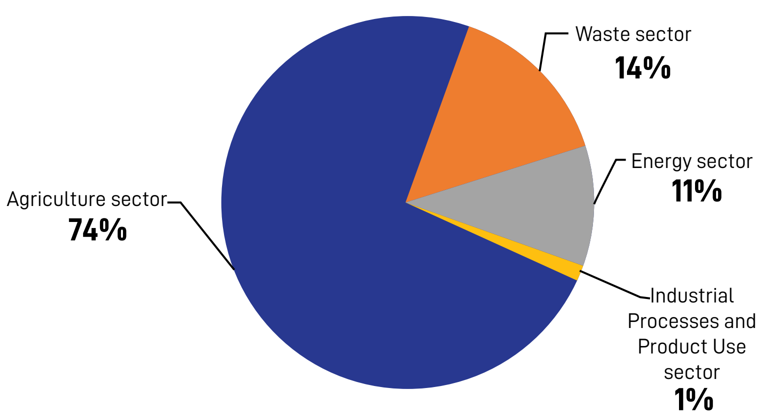
## Issues: Sources of Methane and Mitigation Measures at Present

Methane is primarily released from landfills and wastewater treatment facilities in the waste sector.[4] Waste ends up in landfills where anaerobic decomposition of the organic waste produces methane; while anaerobic digestors in wastewater treatment plants produce methane.[5] The agriculture sector also emits methane, with rice cultivation and livestock being key contributors. Rice is mostly grown in flooded paddies, where anaerobic conditions promote microbial decomposition of organic matter, producing methane, while in the context of livestock, methane is released during the digestion process of the animals, or is a result of poor manure management.[6] Moreover, India's energy sector also contributes to methane emissions, primarily through leaks in natural gas infrastructure like pipelines and storage facilities, adding to the country's methane challenge.[7] As per India's third Biennial Update Report (BUR) that was published in 2021, India's methane emissions in 2016 (excluding LULUCF) were 409 million tone $CO_2e$ of which, 73.96% was from the Agriculture sector, 14.46% from the Waste sector, 10.62% from the Energy sector, and 0.96% was from Industrial Processes and Product Use sector.[8]




**Source: India's third BUR, MoEFCC, 2016**

Figure 1: Annual methane ($CH_4$) emissions in India from Agriculture, waste, energy, and industrial sectors.

In Indian agriculture, ruminants, especially buffaloes, contribute the most emissions: buffaloes are responsible for 42% of livestock methane emissions followed by indigenous cattle (41%) and crossbred cattle (17%).[9] As one of the world's largest rice producers, India also generates considerable methane from flooded rice paddies. West Bengal, Bihar, Madhya Pradesh and Uttar Pradesh, account for 53.9% of the total emissions from the country because of the extensive rice cultivation and the prevalence of flooded rice fields in these regions[10]

India's waste sector contributes to around 14% of the country's total methane output.[11] Wastewater treatment contributes the most methane emissions from the waste sector, accounting for 78.9% of emissions.[12] Landfills, which are the third-largest global source of methane emissions, are responsible for about 21.04% of India's methane emissions from the waste sector.[13]

Much of the methane produced in the energy sector escapes with little effort to utilize it by capturing it even when gas markets are exceptionally tight.[14] India, heavily reliant on coal, emits methane from coal mines during the coal formation process. It is the third-largest methane emitter from coal mines globally, releasing over 2.8 million tons in 2023.[15] Emissions were estimated to be 22 $MtCO_2e$ in 2020 and are expected to reach 45 MtCO2e in 2050.[16]

India's oil and gas industry also contributes significantly to methane emissions. Since January 2022, over 700 methane spikes were recorded near major oil refineries, such as HPCL in Visakhapatnam, Mangalore Refinery, and CPCL in Manali. Regulatory bodies like the National Green Tribunal have noted failures in monitoring methane emissions, exacerbating pollution issues.[17]

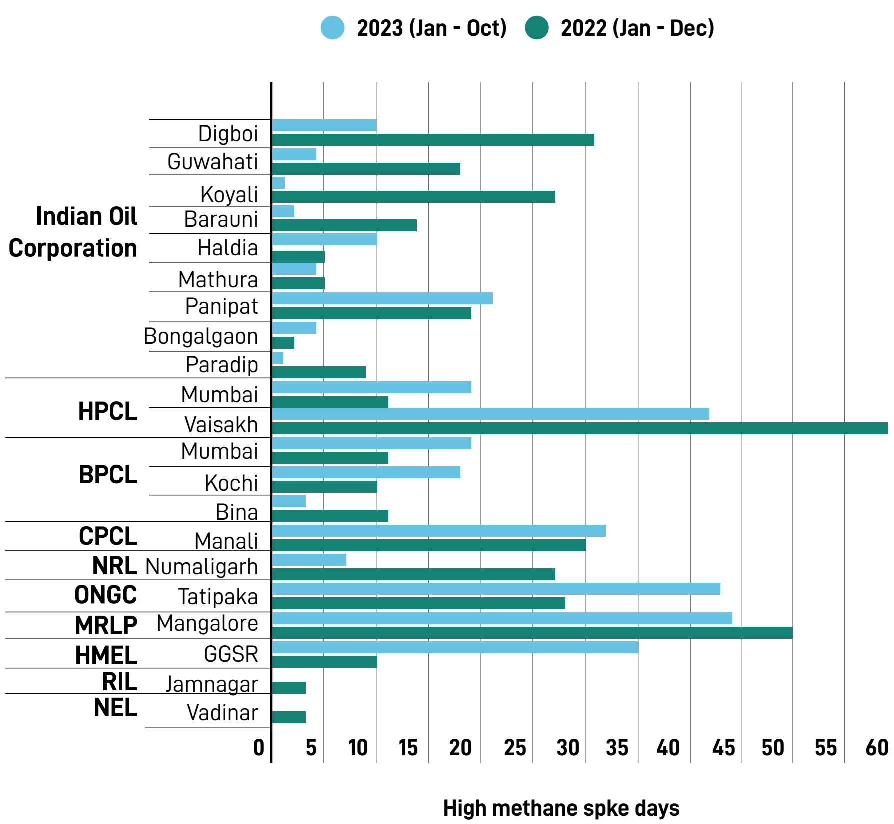



**Fig 2:** Methane spikes near major oil refineries in India

*Source: Chasing Methane: Emission Spikes*

Research in India reveals gaps in accurately quantifying $CH_4$ emissions, particularly at the urban level. While studies have modeled emissions from landfills and industrial activities, continuous and localized monitoring is needed.

India's Nationally Determined Contributions (NDCs) under the Paris Agreement aim for a 33-35% reduction in GDP emissions intensity by 2030.[18] As per India's third BUR to the UNFCCC, methane emissions accounted for 409 million tons CO2e i.e. 14.43% of India's total Greenhouse Gas (GHG) emissions in 2016 making it a key focus for mitigation.[19] The country's National Action Plan on Climate Change, launched in 2008, provides a strategic framework for addressing climate change across India through eight national missions promoting renewable energy, afforestation, and sustainable agriculture. Also very significant is the National Mission for Sustainable Agriculture (NMSA) that targets methane emissions from rice paddies through water-efficient farming techniques.[20] At the state level, each state has developed its SAPCC aligned with the national framework to tackle regional climate challenges. States like Gujarat and Punjab focus on reducing methane emissions from agriculture and livestock through precision farming and biogas programs. Punjab's SAPCC aims to cut agricultural methane emissions via improved crop residue management and alternative biomass uses.[21]

## Challenges

A major challenge in managing methane emissions is the lack of comprehensive data and monitoring infrastructure. Current systems do not capture detailed emissions data from various agricultural sources, which limits effective policy-making and targeted mitigation. Additionally, uncertainties in emission estimates make it difficult to evaluate the impact of current mitigation efforts accurately. There is a strong need for integrated, cross-sectoral approaches to address methane emissions effectively. Coordinating efforts between agriculture, waste management, and energy sectors can maximize synergies, but existing policies often operate in isolation, reducing their impact on interconnected issues of methane emissions and climate change.

In India, agriculture is the largest contributor to methane emissions, with livestock responsible for 63% and rice farming contributing nearly 11% of these emissions.[22] This chart depicts how different animals contribute to methane emissions in the livestock sector in India and how much each animal emits over different periods of time, making livestock an important arena to focus upon to reduce emissions.

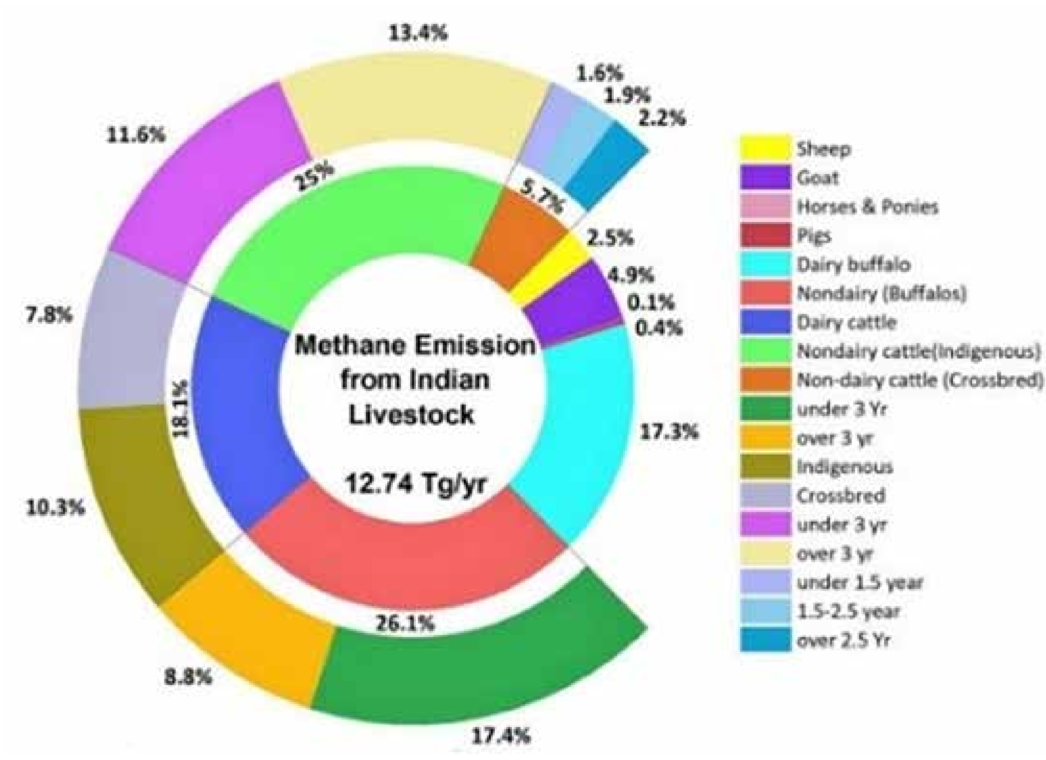



**Fig. 3:** Livestock category-wise Methane emission from the country (2019).
(Tg/yr= Teragram/year)

*Source: Carbonaceous Aerosols in the Atmosphere (III), Aerosol and Air Quality Research*

The livestock sector is integral to the rural economy, providing employment to nearly 8% of the national labor force[23]and contributed about 4.90 percent of total Gross Value Added (GVA) in 2020-21.[24] However, this also presents an unfortunate policy complication. At the heart of the rural economy lies vulnerable rural communities who rely largely on the agriculture sector. They are unable to grasp the heightened impact of methane emissions on their own communities even as they rely on livestock for their livelihood. Further, they also face increased vulnerability to climate change effects such as extreme weather events and food insecurity happening due to greenhouse gas emissions like methane. Addressing this conundrum affecting rural communities in India is vital and requires not only technological advancements and policy changes, but also a deep understanding of the socio-economic dynamics at play.

Therefore, methane mitigation efforts depend on technological innovation, policy interventions, and community engagement; focusing on sustainable agriculture, efficient waste management, and renewable energy. Key technologies include biogas systems for livestock and anaerobic digestion for waste management; with bio-CNG production from agricultural and municipal waste offering a sustainable energy alternative. In addition to technology, strong policies such as carbon pricing, emission standards, and research support are crucial for scaling methane-reducing solutions. Incentives for renewable energy projects like bio-CNG and regulatory measures can promote low-emission technologies. Policies targeting industrial processes and energy efficiency could further reduce emissions.

## Potential Solutions & Way Ahead

For India to reduce its methane emissions, one way is to follow a sectoral approach. For the agriculture sector, biogas systems for livestock is a potential game changer as this will not only control methane emissions but also convert it to useful energy. Applying plant growth regulators can reduce methane emissions in rice paddies. Natural nitrification inhibitors like neem cake help reduce methane emissions as well. Implementing the System of Rice Intensification (SRI) and Alternate Wetting and Drying (AWD) methods can cut methane emissions extensively.[25] Developing low methane-emitting rice varieties, which reduce fertilizer use by 25%, contribute to emissions reduction.[26] Adopting feed additives like Tannins and Bovaer in livestock also helps to mitigate methane production.[27] In the waste sector, practicing source segregation and dumpsite remediation through bioremediation techniques can reduce emissions from legacy waste. Avoiding landfill disposal of biodegradable waste helps prevent methane generation. Upgrading wastewater treatment, where only 28% of sewage is currently treated, can further manage methane from solid waste.[28] Utilizing India's 92 trillion cubic feet of coal bed methane and practicing pre-mining methane drainage can reduce emissions in the energy sector. Enhanced monitoring, reporting, and improving ventilation systems in coal mines can help capture methane, improving safety and reducing fugitive emissions.

### The Namakkal Waste to Energy Project in Tamil Nadu

**The plant converts organic waste into renewable electricity, addressing India's need for sustainable energy solutions. Under controlled conditions, biogas is produced through a bio-methanation process, recovering methane from chicken litter and organic waste. The project processes 120,000 tons of chicken litter and organic waste annually, preventing methane emissions from open storage and contributing to the southern electricity grid. This significantly reduces overall methane emissions.**

**As India's first waste-to-energy project, it serves as a model for similar initiatives in regions with waste management and energy challenges. Its success in converting local organic waste into energy and fertilizer demonstrates a viable approach adaptable to other states in India.**

**Source: The Better India**

## Areas for Further Exploration

India has significant potential to lead in methane reduction through innovative biogas production, smart agriculture, and methane capture. By integrating these strategies into national policies such as the Gobar-Dhan scheme for biogas from organic waste and the NMSA promoting practices like Direct Seeding Rice, India can effectively lower methane emissions. Additionally, urban areas are adopting advanced waste management systems to capture methane from organic waste. To harness this potential, India should invest in research and development and encourage collaboration among stakeholders; ultimately enhancing air quality, food security, and rural livelihoods while setting a global example in sustainable development.

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# TROPOSPHERIC OZONE

## Introduction

Tropospheric or ground-level ozone ($O_3$) is a short-lived climate pollutant that remains in the atmosphere for only hours to weeks.[1] A long-term study in India[2] using satellite and ground-based data has revealed increasing trends in tropospheric ozone over the past few decades. Ozone is a key component of smog, which causes the Air Quality Index levels to reach unhealthy levels on a yearly basis in cities such as New Delhi and across India.[3] Tropospheric ozone is the third-most important greenhouse gas after carbon dioxide and methane. High concentrations of it can lead to breathing problems, premature death in humans, and hinder plant growth.[3]

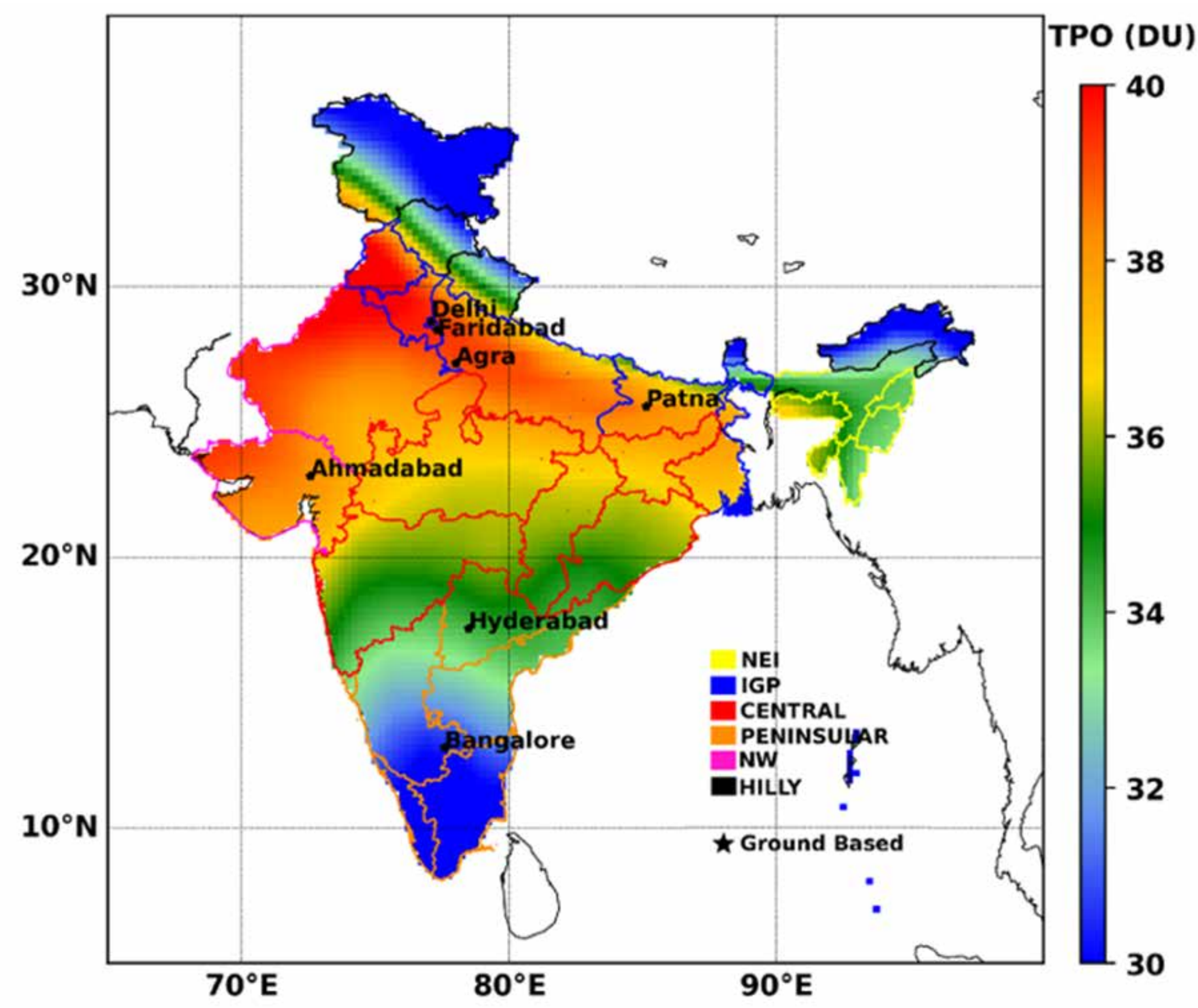


**Fig. 1.** Spatial distribution of tropospheric column ozone (TPO) in India averaged for the period of 2005–2020.

A study from IIT Kharagpur found India's tropospheric ozone has been increasing due to pollution, mainly from rising $NO_2$ and industrial emissions. Northeastern India, the Indo-Gangetic Plain, and Western India show significant increases since the 1980s.[4] Major cities experience ozone spikes especially during the monsoon season. Peninsular India had the highest ozone increase, with the most significant rise during the monsoon season. This has major ramifications since enhanced ozone can warm the climate by 0.2°C to 0.5°C regionally.[5]

| Location | Level of ozone [μg/m³] |
|---|---|
| Chennai[23] | 106 |
| New Delhi[27] | > 160# |
| Pantnagar[12] | 100 |
| Ahmedabad[28] | <160# |
| Hyderabad[35] | 198 in 2002 and 180 in 2003 |
| Kolkata[34] | 96 |
| Chandrapur district[29] | 50 |
| Pune[36] | 120 |
| Anantapur[24] | 104 ± 20 |
| Mt Abu[26] | Background = 66<br>Continental levels =96 |
| Pune, Bandipur, Nilgiris[22] | Annual average = 54 |
| | **Other Measures** |
| Anantapur[32] | Annual average ozone mixing ratio =35.9 |
| Anantpur[15] | Yearly mean mixing ratio^ = 35.9 ± 8.8 |
| Delhi[30] | Threshold exceeded for 45 days /yr |
| Agra[37] | AOT 40 index*<br>Summer- 840 ppb.h<br>Winter- 2430 ppb.h |

**Fig. 2.** Highest ozone level recorded at various stations in India

$O_3$ is a secondary pollutant, meaning that it does not have any direct emissions sources; rather, it is a compound formed by the interaction of sunlight with volatile organic compounds (VOCs) including methane and nitrogen oxides ($NO_X$) which are emitted largely by human activities.[6] Tropospheric ozone primarily comes from two sources: downward transport of ozone from the stratosphere (Stratosphere-Troposphere Exchange, STE), accounting for about 10% of its production[7]; and chemical formation from human-made pollutants like nitrogen oxides ($NO_x$) and hydrocarbons. Natural sources like lightning, biomass burning, and biogenic emissions – in addition to industrial emissions and vehicle exhaust – contribute to ozone formation.

$O_3$ plays a significant role in both atmospheric chemistry and climate change. Near the Earth's surface, it acts as a toxic oxidant, negatively affecting human health, plant life, and overall air quality. Ozone is primarily formed by the photochemical reactions of pollutants like carbon monoxide (CO) and hydrocarbons in the presence of nitrogen oxides ($NO_x$). Its formation is accelerated by high temperatures, dry air, and sunlight. In terms of climate change, tropospheric ozone is a potent greenhouse gas (GHG), contributing to global warming by absorbing outgoing long-wave radiation. Its global radiative forcing ranks third among GHGs, after carbon dioxide ($CO_2$) and methane ($CH_4$).[8]

## Issues

Tropospheric ozone pollution in India arises from a variety of sources including vehicular emissions, industrial activities, and agricultural practices.[9] It poses severe risks to human health, exacerbating respiratory diseases like asthma and chronic bronchitis. Additionally, tropospheric ozone is phytotoxic, affecting vegetation and leading to environmental degradation including the deterioration of grasslands and forests. Furthermore, it plays a significant role in the formation of smog, particularly in densely populated urban areas and industrial hubs.[10]

Being a strong oxidant with the potential to generate photochemical smog, ozone disrupts human respiratory functioning and plant photosynthesis, thereby making its impact multifold. Tropospheric $O_3$ is one of the most concerning air pollutants in the context of India's food security – which is already getting impacted because of the uncertainties of climate change, overpopulation, biodiversity loss, and overutilization of natural resources. It is a major contributor to crop yield losses, as well, in India. A study analyzed the yield loss in rice due to surface ozone pollution in India during 2005–2020, where rice production loss was seen to have increased from 7.39 Million tonnes (Mt) in 2005 to 11.46 Mt. in 2020.[11] Another study indicated that ozone-induced damage has led to wheat yields being 36% lower globally than they could be without pollution , where wheat showed more sensitivity than rice to ozone in chamber experiments.[12]

The IGP is one of India's – and of the world's – most fertile agricultural regions. But it faces severe crop yield losses due to high $O_3$ concentrations, largely from the transport sector and distant sources. Between 2019-2021, ozone-related wheat production losses in select IGP districts reached 3.4 million tons, valued at $923 million.[13] Wheat's Relative Yield Loss (RYL) was 9.3% in 2019, 12.8% in 2020, and 11.3% in 2021 – enough to meet the needs of 11.4 million people. Moreover, achieving WHO's Air Quality Guidelines for ozone could have prevented 11,407 premature deaths in 2021, generating $34 billion in health and economic benefits. In India, the state of Uttar Pradesh saw the greatest losses in both crop yield and premature deaths.[14]

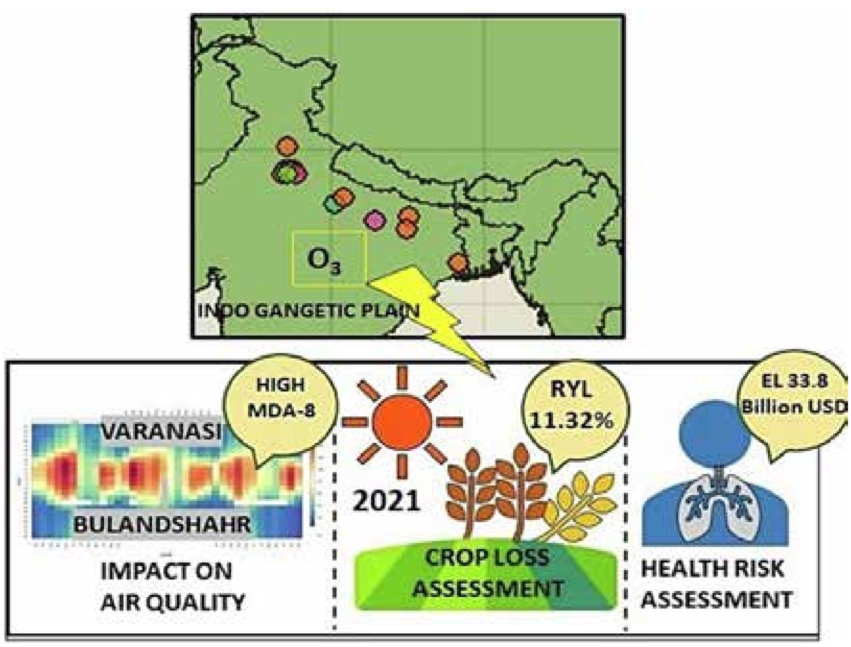


**Fig. 3.** GP Ozone Risk Assessment Infographic

In terms of respiratory illnesses, short term exposure to ozone causes a drop in lung function measures, and it also affects the lung's mucociliary function thereby increasing the susceptibility to bacterial infections. With increase in surface ozone levels, there is likelihood of increased risk for Chronic Obstructive Pulmonary Diseases (COPD), and the number of cardiovascular and respiratory deaths. In children, an increase in ozone concentration is associated with increases in hospital admissions and unscheduled asthma medications.[15]

## Challenges

One of the biggest challenges in managing tropospheric $O_3$ pollution is the complexity of its formation. It involves the interaction of NOx and VOCs, which are emitted from a wide range of sources such as transportation, industry, and agriculture. The chemistry behind ozone formation is highly nonlinear, making it difficult to predict and manage. Moreover, the precursors to ozone are widespread across sectors, necessitating coordinated action between industries, urban planners, and governments.

Tropospheric $O_3$ pollution disproportionately affects urban populations, especially in areas with high industrial and vehicular emissions. Cities like Delhi, Hyderabad, and Bangalore are affected by increased anthropogenic activities. This results in significant changes in ozone levels during monsoon in Delhi, and during the pre-monsoon and post-monsoon seasons in Hyderabad and Bangalore where ozone levels are consistently high, making them major hotspots for respiratory illnesses.[16] Vulnerable groups such as children, the elderly, and individuals with pre-existing health conditions are most at risk from this pollutant. Geographically, the IGP is particularly vulnerable due to its high population density and agricultural activities, making ozone a critical issue for both human health and food security .[17]

Technological innovation and regulatory interventions are crucial for mitigating tropospheric ozone pollution. Cleaner production processes, emission control technologies, and the promotion of efficient transportation systems are necessary to address ozone pollution. Public awareness campaigns that emphasize the importance of reducing vehicle emissions and promoting sustainable urban planning are equally critical. Some regions have started adopting stricter air quality standards, but more coordinated efforts across sectors and regions are needed.

## Potential Solutions and Way Ahead

To manage tropospheric ozone pollution effectively, India must adopt a range of solutions including advanced emission control technologies in industrial and transportation sectors, and the promotion of alternative fuels. Implementation of clean air policies at both national and city levels is essential. For example, efforts in Delhi to ban plastic burning and reduce industrial emissions have shown promise.[18] Additionally, energy-efficient practices and the promotion of cleaner fuels, such as biofuels, can significantly reduce ozone precursors.

International cooperation plays a vital role in addressing tropospheric ozone pollution. Knowledge sharing with global partners and investments in capacity building are essential for scaling up mitigation efforts. Policy instruments such as appropriate market mechanisms and carbon credits can incentivize industries to adopt cleaner technologies. India can also benefit from global initiatives aimed at reducing short-lived climate pollutants like ozone. [19]

### Case Study: Promoting Low-Carbon Transport in Indian Cities by UNEP

**The Promoting Low-Carbon Transport in India initiative, implemented by the United Nations Environment Programme (UNEP) from 2010 to 2015, focused on reducing transport-related emissions, particularly VOCs that contribute to ground-level ozone pollution.**

**The project developed Low-Carbon Mobility Plans for three cities: Rajkot, Visakhapatnam, and Udaipur. These plans emphasized sustainable transport solutions such as enhancing public transit and promoting non-motorized transport options. By advocating for cleaner fuels and improved public transportation infrastructure, the initiative aimed to lower emissions from vehicles, thereby mitigating ozone formation. This approach not only addresses air quality issues but also aligns with broader sustainable development goals by improving public health and fostering economic resilience through investments in green infrastructure. To further advance VOC emission reduction, increased investments in research and development are essential. Enhancing monitoring capabilities for VOCs and ozone levels, developing low-emission technologies, and fostering multi-stakeholder partnerships will be crucial for effectively implementing ozone reduction measures across India.**

## Areas for Further Exploration

Emerging trends in managing tropospheric ozone pollution in India include the integration of air quality monitoring and forecasting systems, development of low-emission transport infrastructure, and the promotion of green urban spaces. For instance, projects under the National Clean Air Programme (NCAP) emphasize real-time air quality monitoring and predictive modelling to inform policy decisions.[20] Additionally, initiatives like the promotion of low-carbon transport systems aim to reduce emissions from the transport sector, which is a significant contributor to ozone pollution.[21] Furthermore, transitioning to low-emission transport can enhance energy efficiency and reduce dependence on fossil fuels, contributing to environmental sustainability.[22] Mitigating tropospheric ozone aligns with broader sustainable development goals in India such as improved public health outcomes, enhanced environmental sustainability, and economic resilience. Reducing ozone levels can lead to better air quality, thereby decreasing respiratory diseases and associated healthcare costs.[23] Advocating for increased investments in research and development initiatives is crucial for advancing ozone mitigation technologies. Enhanced monitoring and reporting capabilities will facilitate effective implementation of reduction measures, while fostering multi-stakeholder partnerships. This, in turn, can drive collaborative efforts towards achieving cleaner air.

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# NITROUS OXIDE

## Introduction

Nitrous oxide ($N_2O$), commonly referred to as laughing gas, is a potent greenhouse gas and an ozone-depleting substance (ODS) that occurs naturally in the environment. $N_2O$ molecules persist in the atmosphere for an average of 121 years before being removed by natural sinks or destroyed through chemical reactions. This persistence poses five key threats to greenhouse gas balance, water, air, soil quality, ecosystems, and biodiversity.[1] Similar to carbon dioxide ($CO_2$), $N_2O$ is a long-lived greenhouse gas, with an atmospheric lifetime of approximately 121 years. However, its Global Warming Potential (GWP) is 273 times greater than that of $CO_2$ over a 100-year time horizon.[2] Mitigating $N_2O$ emissions could potentially save 20 million lives globally by mid-century. In the absence of any mitigation strategy, $N_2O$ could also emerge as a dominant driver of climate change as efforts to reduce $CO_2$ and methane emissions, the current leading contributors, begin to take effect.[3] Further, if $N_2O$ emissions continue to rise, they may reverse decades of progress in ozone layer restoration, which protects the Earth from harmful ultraviolet (UV) radiation.

Emissions of $N_2O$ in the atmosphere have exhibited growth rates from 2020 to 2022 that are higher than any previously observed year; and approximately 30% higher than the average of the previous decade. In 2020, the top five countries by volume of anthropogenic $N_2O$ emissions were China (16.7%), India (10.9%), the United States (5.7%), Brazil (5.3%), and Russia (4.6%).[4]

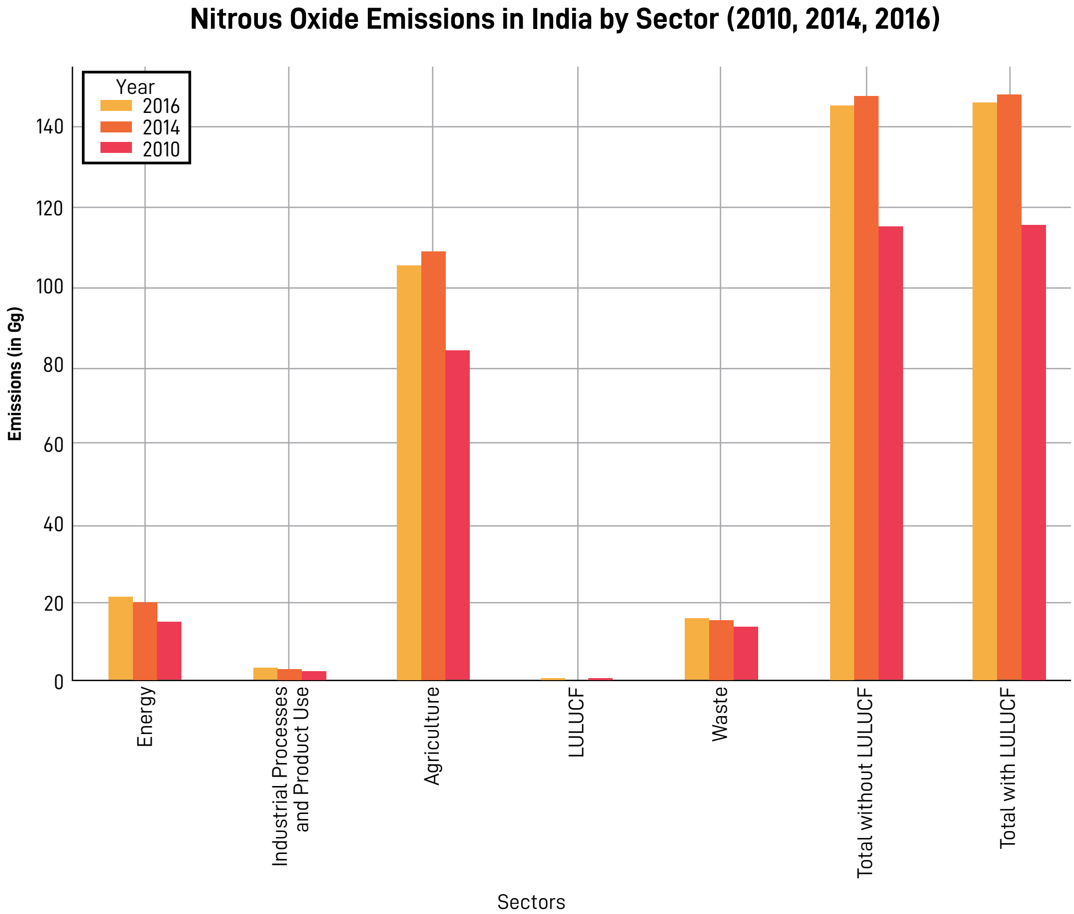


**Figure 1:** Sectoral $N_2O$ emissions in India (2010-2016)
*Source: Biennial Update Reports of India*

According to India's third Biennial Update Report (BUR), submitted to the UNFCCC in February 2021, the country's total greenhouse gas (GHG) emissions in 2016, excluding emissions from Land Use, Land-Use Change, and Forestry (LULUCF), amounted to 2,838.89 $mtCO_2e$, while emissions including LULUCF were 2,531.07 mtCO2e.

Nitrous oxide ($N_2O$) emissions, a significant component of India's total GHG emissions, predominantly arise from the agriculture, energy, waste, forestry, and industrial processes and product use (IPPU) sectors. Across all BUR submissions for the years 2010, 2014, and 2016, agriculture consistently emerged as the largest contributor to $N_2O$ emissions with an increase of 26% from 2010-2016. The energy sector's $N_2O$ emissions grew by 40% between 2010 and 2016. In contrast, emissions from industrial processes and waste remained relatively stable, exerting minimal impact on the overall $N_2O$ emission levels. Figure 2 illustrates the sectoral distribution of India's $N_2O$ emissions.

## Issues: Key Sources & Ongoing Initiatives to Counter $N_20$ Emissions

South Asia is one of the most densely populated regions globally, and a significant hotspot for $N_2O$ emissions. While agriculture has traditionally been the dominant sector, the region is now witnessing a rapid shift towards industrial and energy-related activities, which are poised to become major sources of future $N_2O$ emissions. Among South Asian countries, in fact, India leads in $N_2O$ emissions, producing approximately 34 Gg $yr^{-}1$, largely in line with its size, population, and fuel consumption.[5]

**Agriculture:** The agriculture sector is the primary contributor to global $N_2O$ emissions, with nitrogen fertilizer application – including livestock production and manure management – being the largest anthropogenic source. Over the past decade, agricultural activities have been responsible for over 70% of total anthropogenic $N_2O$ emissions[6]. India's agriculture sector is responsible for approximately 14% of the country's GHG emissions. Within this sector, enteric fermentation accounted for 54.6% of emissions, followed by rice cultivation at 17.5%, fertilizer application to agricultural soils at 19.1%, manure management at 6.7%, and field burning of agricultural residues at 2.2%. Regionally, South Asia, Africa, and Latin America have dominated the rise in global emissions since the 1990s. India recorded the highest emissions at 329 Gg N $year^{-1}$, followed by China (267 Gg N $year^{-1}$), the United States (163 Gg N $year^{-1}$), Brazil (129 Gg N $year^{-1}$), and Pakistan (102 Gg N $year^{-1}$) during the 2010s.[7]

According to World Bank data, an increasing trend in agricultural $N_2O$ emissions is evident, with the latest data from 2020 indicating emissions of 239,729 $tCO_2e$. This increase is primarily attributed to direct nitrogen additions in agriculture.[8] The over-application of nitrogen fertilizers leads to significant rises in direct soil $N_2O$ emissions, as plants can only absorb a fraction of the nitrogen from synthetic fertilizers, leaving approximately 50% to either pollute water sources or be converted into $N_2O$ by soil bacteria.[9] In India, estimated $N_2O$ emissions from agricultural soils are around 250 Gg of $N_2O$, with inorganic fertilizers contributing to over 75% of these emissions[10].

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**Waste:** In 2016, the waste sector accounted for 2.7% of total GHG emissions, increasing by 4% in 2018. Over this period, emissions grew at a CAGR of 2.02%, from 2005 to 2018. The primary sources of GHG emissions within this sector are municipal solid waste, domestic wastewater, and industrial wastewater. Notably, India's rural areas contribute significantly more to the country's total $N_2O$ emissions from domestic wastewater compared to urban areas. Rural emissions amounted to 132.8 $MtCO_2e$, nearly twice that of urban emissions, which were recorded at 66.7 $MtCO_2e$.[12]

Domestic wastewater encompasses human sewage mixed with other household wastewater, such as effluents from showers, sinks, and washing machines[13]. The degradation of nitrogenous compounds (urea, nitrate, and proteins) in wastewater results in N2O emissions. The characteristics of domestic wastewater—and the resulting GHG emissions—vary across regions depending on factors like economic conditions, dietary patterns, water supply infrastructure, treatment systems, and local climate. In India's rural areas, wastewater management systems are largely absent, with collection, transportation, treatment, and disposal rarely practiced, thus leading to increased emissions.

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## National Initiatives

The Government of India has implemented numerous programs and policies to mitigate $N_2O$ emissions. These efforts are part of a broader strategy highlighted by the South Asian Nitrogen Hub, which identifies 132 policies dedicated to sustainable nitrogen management in the country.[14] Key initiatives include the National Mission on Sustainable Agriculture (NMSA) under the

National Action Plan on Climate Change (NAPCC), aimed at promoting ecologically sustainable and climate-resilient agricultural practices nationwide. The recent Neem-Coated Urea scheme exemplifies these efforts, leveraging organic neem oil to enhance nitrogen use efficiency, reduce soil and water contamination, and deter non-agricultural diversion of urea.[15]

Additionally, the Commission for Agricultural Costs and Prices (CACP) has recommended bringing urea under the Nutrient-Based Subsidy (NBS) regime to manage its affordability and curb overuse in agriculture.[16] The National Innovations in Climate Resilient Agriculture (NICRA) further contributes by developing technologies such as soil test-based nitrogen application, zero tillage, crop residue management, organic manure use, and crop rotation with legumes, all aimed at reducing $N_2O$ emissions.

## Challenges

Several challenges persist in mitigating $N_2O$ emissions, despite the availability of abatement technologies. First, concerns remain about the effectiveness of these technologies, as they often fail to address the root causes of emissions. The over-application of nitrogen-heavy fertilizers, driven by urea subsidies and outdated policies, has contributed to rising $N_2O$ emissions in agriculture. Current fertilizer guidelines are inadequate, neglecting regional soil and crop variations, thus leading to nutrient imbalances particularly in nitrogen use. Although policy reforms such as the 2010 Nutrient Based Subsidy (NBS) scheme have been introduced, nitrogen application remains disproportionately high, and emissions continue to rise.[17]

Additionally, there is a significant gap in accurately quantifying total $N_2O$ emissions and the contributions of different pathways, alongside a need for a simple, reliable model to assess the benefits of mitigation strategies.[18] The South Asian Nitrogen Hub has been providing recommendations for assessing $N_2O$ strategies and policies with a quantitative lens in addition to the undergoing qualitative policies.[19] For wastewater treatment plants (WWTPs), tailored risk assessments are needed including long-term, full-scale trials to evaluate the costs and effects of nutrient removal. Overcoming these challenges will enable the development of novel strategies such as enhancing $N_2O$ reduction through denitrification or low-emission microorganisms. While $N_2O$ mitigation research has advanced, the reliability of these strategies and the potential risks to nutrient removal performance remain significant hurdles to broader implementation at scale.[20]

## Potential Solutions

Internationally, three key multilateral processes assume significance for global $N_2O$ abatement efforts. First, under the UNFCCC, countries report $N_2O$ emissions and may include them in their Nationally Determined Contributions (NDCs), though most prioritize $CO_2$ and $CH_2$. Second, the Montreal Protocol (MP) could also support $N_2O$ reduction due to its role in ozone depletion. Third, UNEA Resolution 5.2 (2022) calls for national action plans to reduce nitrogen waste, potentially addressing $N_2O$ emissions from industry and energy sectors.[21]

In South Asia, efforts to manage nitrogen pollution began with the 2008 establishment of the South Asian Nitrogen Centre (SANC), which led to the Delhi Declaration (2010) and the recognition of nitrogen challenges at COP11. A 2013 study by the South Asia Co-operative Environment Programme (SACEP) on nutrient pollution highlighted knowledge gaps in marine ecosystems. Regional initiatives were reinforced through UNEP's International Nitrogen Management System (INMS) project and culminated in the 2019 Colombo Declaration, where South Asian nations committed to halving nitrogen waste by 2030. The South Asian Nitrogen Hub (SANH), funded by UKRI, now unites institutions across the region to tackle nitrogen challenges.[22]

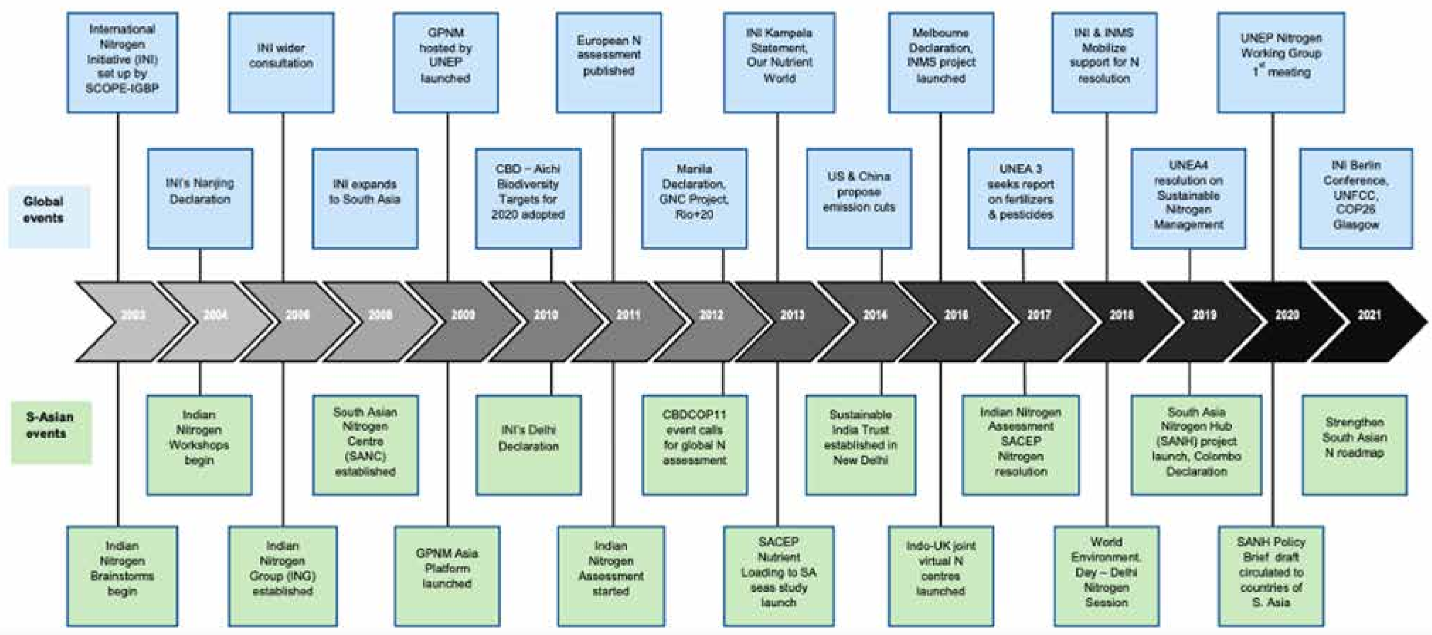


**Figure 1:** Figure 2: Timeline of Global and South Asian developments toward global cooperation on sustainable nitrogen management
*Source: The South Asian Nitrogen Hub*

## Agriculture

Agricultural abatement strategies are often organized around the "4Rs" framework: applying nitrogen at the **optimal rate** (the most cost-effective quantity), at the **right time** (aligned with the crop's peak nitrogen demand), using the **right source** (minimizing reliance on anhydrous ammonia), and placing nitrogen in the **right location** (such as incorporating N bands into the soil)[23]. Research by the Environmental Defense Fund (EDF) in India, shows that reducing excess nitrogen application can lower $N_2O$ emissions while maintaining or improving yields and profits.[24] Similarly, The Royal Society highlights that better fertilization strategies can enhance fertilizer use efficiency and reduce $N_2O$ emissions[25]. Studies in the Indo-Gangetic Plains suggest optimal nitrogen rates of 120–200 kg N $ha^{-1}$ for rice and 50–185 kg N $ha^{-1}$ for wheat are both productive and sustainable. [26] However, strategies like intermittent flooding in rice cultivation may inadvertently increase $N_2O$ emissions, underscoring the complexity of mitigating agricultural emissions. Adopting Site-Specific Nutrient Management (SSNM) can improve nitrogen use efficiency, though its adoption in the Global South remains limited due to cost and complexity.[27] While certain SSNM tools have been developed for smallholder farmers, such as the International Rice Research Institute's web-based Rice Crop Manager, these tools have seen limited adoption due to ongoing challenges related to affordability, usability, and scalability.[28]

## Leaf Color Chart

A simple and effective tool to assess the nitrogen requirements of a crop is a Leaf Color Chart (LCC), a plastic, ruler-shaped strip with four panels ranging from yellowish green to dark green.[29] Evidence suggests that the LCC is a promising, low-cost intervention that supports farmer-led decision-making and helps reduce excessive nitrogen use in India.[30] Similar LCC trials have been conducted in different parts of not just India but Bangladesh[31], China, Philippines, and Vietnam, which have all shown promising results and outputs with reduced fertilizer usage and higher yields.

## Case Study: LCC Project in Gujarat by Precision Development (PxD) and IGSD

PxD conducted a pilot project with Leaf Color Charts in Gujarat, India, in the cotton cropping system. Cotton is one of India's most important commercial crops and requires several fertilizer applications, creating an ideal opportunity for a nitrogen fertilizer intervention. The project encouraged the use of LCCs with 830 cotton farmers and tested several different in-person distribution channels.

*Impact Observed*

**01** Wide usage of the tool among farmers

**02** Strong support for the theory of change that LCCs substantially reduce the use of nitrogen fertilizers without reducing yields.

**03** The farmers who received LCCs, on average, reported applying 35% less nitrogen fertilizers, and harvesting 11% more cotton, than those who did not receive LCCs.

**04** The study estimates that farmers will experience at least a 4.3% decrease in their cost of production per acre if they receive an LCC compared to farmers who do not receive an LCC.

# Areas for Further Exploration

Industrial nitrous oxide is produced as a byproduct in the manufacturing of chemicals like nitric acid (used for fertilizers) and adipic acid (used for nylon and other synthetic products).[32] Under the Kyoto Protocol's Clean Development Mechanism (CDM), countries with emission-reduction commitments can implement projects in developing nations and earn certified emission reduction (CER) credits. As of December 31, 2023, 3,617 of 7,842 registered CDM projects globally have been issued CERs, with India having the second-highest number of registered projects after China.[33]

## Successful $N_2O$ Abatement Projects

Shortly after the CDM was announced, India developed two successful N2O abatement projects in Gujarat and Maharashtra.

### Gujarat Narmada Valley Fertilizer Company (GNFC) $N_2O$ Abatement Project[34]

**The Gujarat Narmada Valley Fertilizer Company is a joint sector enterprise promoted by the Government of Gujarat and the Gujarat State Fertilizers & Chemicals Ltd. (GSFC). The company with their $N_2O$ abatement plant has been able to reduce 3,32,947 mtCO2e per annum with 41,493 CERs credited to them.**

### Deepak WNA 4 $N_2O$ Abatement Project[35]

**Deepak Fertilizers and Petrochemicals Corporation Limited (DFPCL) launched a 'clean development mechanism project' at its manufacturing plant in Taloja, Maharashtra. The company has been able to abate 81,910 $mtCO_2e$ per annum.**

India ranks second in the number of registered CDM projects, but $N_2O$ abatement remains underdeveloped in many countries. To limit warming to 1.5°C by 2100, $N_2O$ emissions must be reduced by a median rate of 11% in the next decade and 25% by 2050. Achieving these reductions requires technological advancements across sectors and policy support through market-based mechanisms.[36] The status of implemented $N_2O$ abatement technologies for nitric acid is not fully understood. For the 500 to 600 nitric acid plants that exist globally, there is no comprehensive inventory discussing implemented abatement technologies and installation of these technologies remains a significant hurdle across the world due to the lack of technology transfer.[37] Besides, one of the widely debated issues has also been the transition from CDM to Article 6.4 mechanism (often referred to as the Sustainable Development Mechanism (SDM)) of the Paris Agreement. Developing countries have been pressing for acceptance of transitional arrangements, there is a stiff resistance from many developed countries on grounds of environmental integrity[38]. Thus, the intersection of international agreements, technology transfers and assistance can aid in exploring climate mitigation for areas which are projected to increase climate risks in future.[33] Chaturvedi A., (2020) Rapid Assessment of the CDM and VCM Portfolio Report of India, Ministry of Environment Forest and Climate Change & DEUTSCHE GESELLSCHAFT FÜR INTERNATIONALE ZUSAMMENARBEIT (GIZ), 15.

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# HYDROFLUOROCARBONS

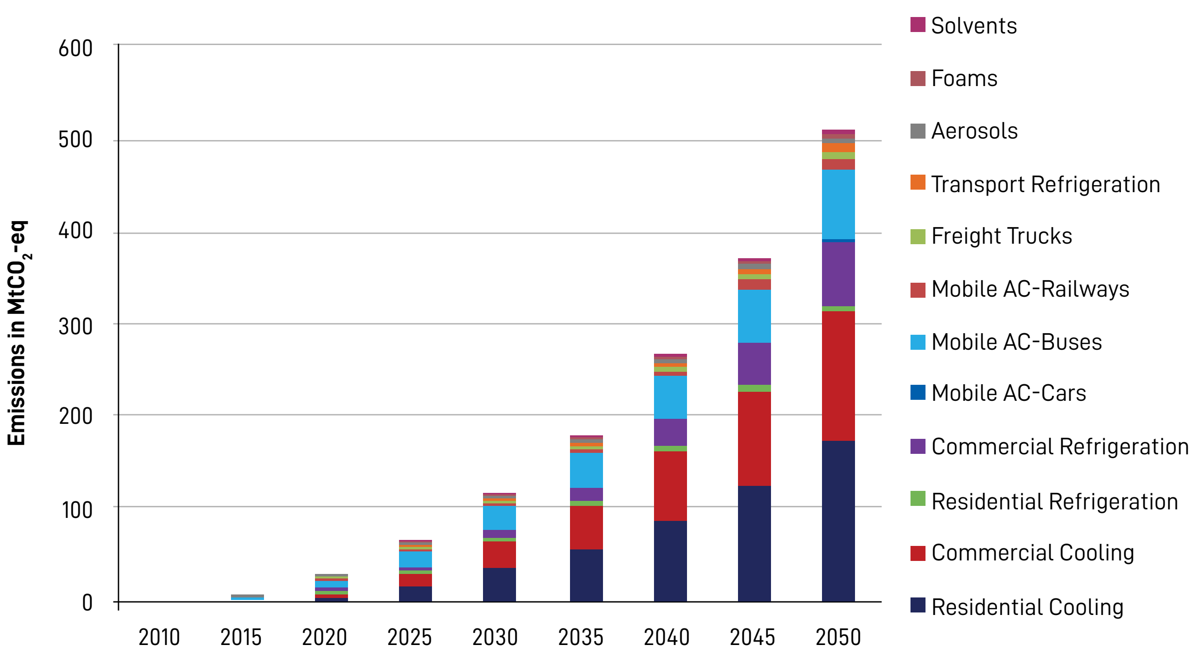
## Introduction

Hydrofluorocarbons are man-made gases that were once essential to replace ozone-depleting substances, but today are no longer needed in most sectors, including air conditioning, refrigeration, and foam insulation. Scientific evidence shows that HFCs, while safe for the ozone layer, have a high global-warming potential and pose a significant challenge to climate change mitigation efforts. This chapter delves into the rapid rise of hydrofluorocarbons in the Indian context. It explores the primary drivers of HFC demand in the country, their environmental impact, and the critical need to phase down emissions under international agreements like the Kigali Amendment. It also highlights the challenges and barriers in transitioning to low-GWP alternatives, emphasizing the need for technological advancements, regulatory support, market mechanisms, capacity-building support and international cooperation to achieve India's climate targets. Overall, the transition to low-GWP alternatives is a low-hanging fruit that will not only reduce emissions but also position India as a leader in climate-friendly technologies, aligning with its global obligations and supporting sustainable economic development.

## Issues

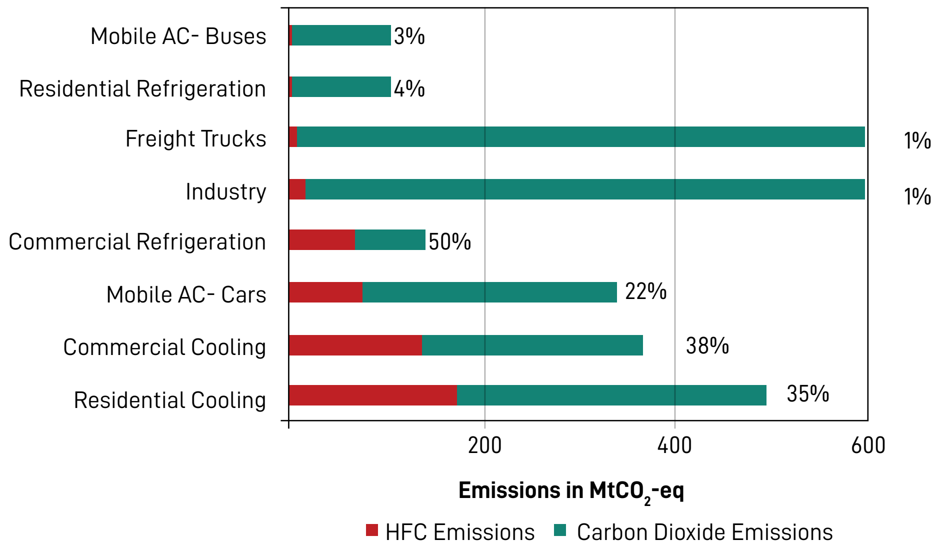
**HFCs are the fastest-growing pollutant, with significant impact on global warming despite their short-lived nature and relatively small share in total GHG emissions.** HFCs are potent, short-lived climate pollutants with an average atmospheric lifetime of 15 years. Although they make up only 2% of global greenhouse gas emissions[1], their global warming potential ranges to over 12,000 times that of $CO_2$[2]. With a growth rate of 10-15 percent per year[3], HFCs are the fastest-growing greenhouse gas globally. In India, the emissions are projected to surge to approximately 503 $MtCO_2$-eq by 2050[4]. Overall, these will account for 5.4% of India's total $CO_2$ and HFC-related global warming impact, up from 3.9% between 2015 and 2050. Half of this global warming impact is projected from the commercial refrigeration sector alone.

**Figure ES1: India's long term HFC emissions across sectors**




Source: CEEW analysis

**Figure ES2: Share of global warming impact of HFC emission in sectoral GHG emissions in 2050**




Source: CEEW analysis

**Rising temperatures, electrification, growing incomes and rapid urbanization have primarily driven the demand for HFCs in India.** Estimates[5] suggest that India's annual HFC demand under current market trends could reach 76 MMT $CO_2$-equivalent ($CO_2$e) in 2030 and 197 MMT $CO_2$e in 2050, from 23 MMT $CO_2$e in 2020, with no change to the current mix of HFCs. A majority of this demand consists of cooling, wherein Direct Stationary Space Conditioning (RACs, DX, and VRF) and Mobile Air Conditioning (MAC)[6] together account for nearly two-thirds of the Indian HFC market. The remaining one-third of demand is divided between chillers, small and large refrigeration systems, foam blowing agents, and cold chains. However, despite rising demand, India's per capita refrigerant use is just 21 grams, far lower than developed countries such as the U.S. which has a per capita refrigerant use of 430 grams, the highest worldwide.[7]

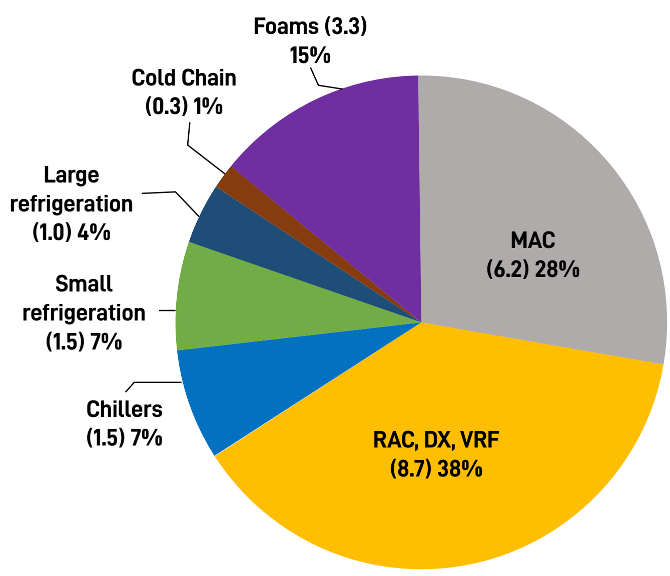



**Figure 2:** Estimated HFC demand by sector in India in 2020 (MMT $CO_2$e)

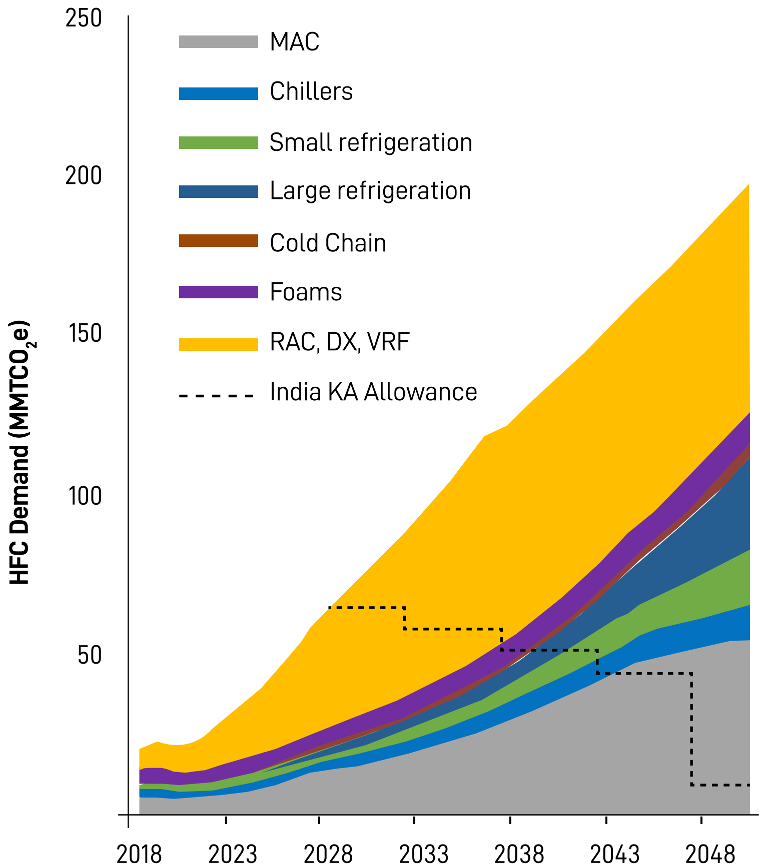



**Figure:** Projected HFC demand for Market Trends secnario-all sectors

**Reducing HFC emissions is key for achieving India's emission intensity targets and fulfilling international obligations under the Kigali Agreement.** Under the Paris Agreement, India has committed to reduce its emissions intensity to 45 percent by 2030 from its 2005 level under its Nationally Determined Contribution (NDC). Additionally, it ratified the Kigali Amendment in 2021 to phase down the use of HFCs, committing to reducing HFC production and consumption in four steps, starting from 2032, to achieve an 85% reduction by 2047 compared to 2024 levels.[8] Failure to phase down emissions could result in an estimated 500 $MtCO_2$-eq of HFC emissions by 2050[9], which would significantly hinder India's ability to meet its climate goals. Delaying phase-down and freezing of HFCs any further will lead to higher mitigation costs with significant socio-economic repercussions.

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## Main Challenges

**The current market penetration of low-GWP alternatives to HFCs remains low.** There are several alternative refrigerants with lower or near-zero global warming potential, including hydrocarbons like propane (R-290) and isobutane (R-600a), ammonia (R-717), carbon dioxide (R-744), and new hydrofluoro-olefin (HFO) refrigerants such as R-1234yf and R-1234ze(E) and their blends.[10] However, gaps persist with respect to application processes, standards, and usage patterns of refrigerants for the Indian market, as are the costs, maintenance requirements, and the technical feasibility standards for their large-scale adaptation and adoption. As a result, HFCs continue to dominate the Indian market today.

The major demand-side barriers[11] responsible for it are high upfront costs, safety concerns, low consumer awareness, and lack of financial incentives. On the supply side[12], manufacturers struggle with high capital costs, nascent R&D, lack of clear safety standards and benchmarks, inadequate government subsidies and difficulties in retrofitting existing systems.

**Table: Current HFC Refrigerants & Scope for Potential Alternatives in India**

| Application | Current HFC Refrigerant | GWP | Alternatives | GWP | Cost Comparison | Barriers | Opportunity |
|---|---|---|---|---|---|---|---|
| **Domestic Refrigeration** | R-134A, R-22 | 1300 | R-600a, R-290 | < 5 | Comparable, high potential of long-term gains offsetting costs | Flammability concerns | **Low-GWP refrigerants** like R-600a and R-290 improve energy efficiency, lowering operational costs and energy bills.<br>**Integrated cooling systems** in industrial and commercial settings also help reduce energy use and cooling demands, offering further savings. |
| **Commercial & Industrial Refrigeration** | R-22, R-134a, R-143a, R-125, R-407c | Varies | R-170, R-1270, R-717, R-1234ze(E), R-744, R-152a | <1-10 | Higher initial costs | Flammability, toxicity (R-717), equipment compatibility | Potential for reduced operational costs and lower emissions |
| **Room Air Conditioners** | R-22, R-410a | 2088 | R-32*, R-290 | 675, <5 | Slightly higher than R-22 | Flammability and safety regulations | Energy-efficient alternatives with significantly lower GWP |
| **Commercial Air Conditioners** | R-22, R-134a | Varies | R-32* | 675 | Slightly higher than R-22 | Flammability concerns | Improved energy efficiency and regulatory compliance |
| **Mobile Air Conditioners** | R-134a, R-22 | 1300 | R-1234yf, R-152a<br>HFO-1234yf, $CO_2$, HFC-152a | 4-10 | 10-15 times costly than current HFC refrigerants | High upfront costs of R-1234yf<br>Flammability characteristics of both R1234y and R152a | **Optimizing airflow around condensers** and using lightweight insulation enhances MAC efficiency.<br>**Reducing refrigerant charge** and improving pipeline design can lower emissions.<br>**The Secondary Loop MAC (SL-MAC)** system is ideal for EVs and HEVs, reducing refrigerant use and leakage risk. |
| **Foams** | - | - | $CO_2$, Propane, HFC-152a, HFC-1234ze | <1-10 | Generally comparable | Compatibility with existing production equipment | Availability of cost-effective and environmentally friendly blowing agents. |

*Source: Author's analysis from various sources*

**High upfront costs deter both manufacturers and consumers from large-scale manufacturing and adoption.** For transition from HFCs to climate friendly alternatives[13], manufacturers need to invest in R&D, buy patented refrigerant technologies, and incur costs for component upgrades and even equipment replacement to accommodate non-HFC refrigerants. This raises the cost for manufacturing and reduces profit margins. In the absence of adequate government support and market incentives[14], this deters manufacturers from large-scale production. As a result, low-GWP alternatives are either absent or far costlier than current HFC refrigerants in India, sometimes even 10-15 times[15].

This substantial price difference exists even for consumers. Interestingly, a recent consumer survey[16] showed that while 75 per cent of AC buyers wanted to purchase a high-star-rated energy-efficient AC with a low GWP, only 14 per cent actually ended up buying one, citing higher upfront costs as the deterrent. In the absence of dedicated consumer financing mechanisms and awareness programs about energy efficiency gains and short payback periods[17], this trend is likely to persist.

**Technology gaps in India's refrigerant manufacturing and import dependence further leads to supply-chain shortages.** There is a lack of domestic manufacturers of HFC-free equipment. In most cases, spare parts have to be imported from other countries as domestic industries struggle to overcome knowledge gaps and achieve scale. Even the more mature industries such as air conditioning are highly fragmented, import-dependent and dominated by small and medium industries (SMEs).[18] In 2017, Hindustan Unilever Limited[19] reported that it had to face almost a year's delay in finding a supplier of hydrocarbon refrigerant in India with the necessary licenses and permits to import the refrigerant, thus discouraging it from HFC-free transition.

While the situation is expected to have improved, most of the low GWP alternative refrigerants continue to be heavily patented and costlier than the existing refrigerants in use[20]. The majority of private manufacturers have low research-to-investment ratios[21] due to the commodity-based nature of materials, slow adoption of new technologies, and low profit margins. The India Cooling Action Plan (ICAP) also does not identify natural refrigerants as an essential need for India's refrigerant transition and thus does not promote public R&D demonstration projects. Limited awareness amongst smaller enterprises, retrofitting difficulties and lack of adequate financial support[22] further hampers domestic manufacturing.

**Even when available, many of these alternatives are either flammable and toxic or operate at very high pressures, thus limiting their widespread adoption.** Natural refrigerants such as ammonia, carbon dioxide and hydrocarbons (HC)[23] serve as climate-friendly, cost-efficient alternatives but raise significant safety concerns. Managing flammability risks of these alternatives, ensuring their effective performance at high temperatures, and guaranteeing safety in densely populated urban cities such as New Delhi and Mumbai is crucial for their successful deployment. These risks require a robust system with appliance safety standards and benchmarks.

While the Bureau of Indian Standards' (BIS) adoption of safety standards for natural refrigerants under IEC 60335-2-40:2018 and MED was a significant welcome step, stakeholder interactions have revealed that safety concerns continue to persist. The main barriers to safety standards for low-GWP refrigerants[24] include the lack of on-ground implementation strategies, absence of standardization for large-scale cooling systems using natural refrigerants, and challenges related to safely installing systems like VRF units that require large quantities of refrigerants in occupied spaces. In addition, the safety hazards associated with these refrigerants necessitate notable adjustments in design and operational practices[25], which in turn increases the overall cost and discourages the adoption of natural refrigerants at scale.

**Around 40% of annual HFC consumption in the servicing sector is due to recharging devices that leaked during operation, indicating the need to invest in formal training programmes for the workforce to reduce leakages.** Many refrigeration and air conditioning systems have relatively high rates of leakage. As a result, more than half of total HFC emissions[26] come from topping up refrigerant lost through gradual leakage or more major total loss incidents. Effective installation, servicing and reclamation[27] are key for reducing these leakages. However, lack of consumer awareness about servicing and absence of a skilled, trained workforce for servicing prevents timely HFC mitigation. At a macro level, key challenges in training service technicians[28] include limited access to formal training, informal nature of the workforce, lack of standardization and proper certification, particularly in the largely informal RAC servicing sector. In addition, end-of-life recovery of refrigerants[29] is also minimal in India due to a lack of regulations, limited awareness, poor infrastructure, and insufficient incentives.

**Overall, HFC phase-down is a multi-institutional regulatory challenge requiring concerted action across stakeholders.** The good news is that although HFCs are extremely potent, they only remain in the atmosphere for about 15 years, so their concentrations[30] can be reduced soon after emissions are cut. While several low-GWP models may not be commercially feasible in the country today, these highly efficient, low-GWP models have shown immense success in other geographies and are sometimes cheaper than lower-efficiency models[31], even on a first-cost basis. Even when they increase the retail price, the payback period is usually short.

Shifting to low-GWP alternatives from high-GWP HFCs offers energy savings, reduced emissions, and economic benefits for India, while aligning with international market trends and potentially the option of covering mitigation costs through support from the Montreal Protocol's Multilateral Fund.

## Potential Solutions & Way Ahead

India has significant potential to reduce HFC emissions by nearly 98%[32] through the adoption of low-GWP refrigerants. Approximately 37% of this reduction could be achieved at zero cost, with an additional 53% attainable at under €20 per ton of $CO_2$ equivalent. By transitioning HFC-free commercial refrigeration[33] by 2030, India could cut emissions by 7 million metric tons of $CO_2$ equivalent—akin to removing 1.5 million cars from the roads annually. However, this transition to low-GWP refrigerants in India will require strong government incentives, innovative business models, skilled workforce, robust market mechanisms, along with technical and financial cooperation by international partners.

**Given the cost-effectiveness of mitigating HFC emissions in the RAC and industrial refrigeration sectors, prioritizing low-GWP alternatives in these areas is vital.** Some of the mitigation potential in several sectors, including in stationary air-conditioning and industrial refrigeration,[34] is expected to come at a zero or negative marginal cost, thus providing India an opportunity to take appropriate action. With the Indian RAC industry already embracing HFC-32, which now dominates over 90% of the market, there's an opportunity to shift to even lower-GWP options like R-290 by 2030, or ideally by 2025 for accelerated phasedown efforts. Internationally, the Mobile Air Conditioning (MAC) sector[35] has led HFC reduction efforts. India is well-positioned to

follow suit, particularly as HFO-1234yf, a viable HFC alternative, is produced domestically. Pilot studies have also shown that HFC-152a-based secondary loop systems[36] could be a feasible alternative for MAC systems.

**Government incentives will play a crucial role in accelerating this transition.** European Union grants have demonstrated success, and similar policies in India could aid manufacturers in adopting low-GWP refrigerants. Although Indian policies focus primarily on energy-efficient appliances, the Cooling India Action Plan (ICAP) emphasizes the need for manufacturer-focused initiatives. Potential incentives could include debt-linked support, such as soft loans to assist small and medium enterprises with upgrading their facilities to produce eco-friendly equipment. Additionally, eco-labeling could integrate both energy efficiency and refrigerant impacts into a single metric, expanding the current S&L program to address direct and indirect GHG emissions. Incentive programmes for sellers could further accelerate the sale of low-GWP alternatives.

**Market mechanisms, including bulk procurement and sustainable business models, will be essential to generating demand for low-GWP refrigerants.** The Cooling-as-a-Service (CaaS) model offers an innovative approach by providing customer-centric cooling solutions that address environmental and social considerations while reducing equipment maintenance costs. Public procurement can further promote low-GWP cooling appliances.

**Finally, international cooperation, particularly in R&D and technology transfer, will be indispensable.** Collaborations across industries, government, and academia can maximize resources, expedite learning, and facilitate technical expertise transfer. Leveraging global initiatives like the IEA Technology Collaboration Programmes can foster advancements in sustainable cooling solutions across regions, thereby accelerating India's shift towards low-GWP refrigerants. Overall, support through multilateral, grace periods and support in accessing patented technologies will be crucial.

**In conclusion, transitioning from HFCs to low-GWP refrigerants offers a strategic opportunity for India to reduce greenhouse gas emissions, fulfil international climate commitments, and drive sustainable economic growth.** This shift requires comprehensive efforts, including government incentives, innovative business models, enhanced workforce training, and international cooperation in R&D and technology transfer. By investing in low-GWP solutions, India can become a leader in climate-friendly technologies, strengthen its industrial competitiveness, and address urgent environmental and social challenges, paving the way for a sustainable and resilient future.

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# BLUEPRINT FOR THE FUTURE

## Introduction

Given the wide range of impacts from short-lived climate pollutants in India, the societal, economic, and environmental benefits of fast action are numerous and far outweigh the costs. The good news is that several readily available, low-cost, targeted measures for tackling non-carbon dioxide emissions exist and have even demonstrated success in similar geographies. Given that most of these pollutants have a short atmospheric lifespan, significant climate and clean air benefits can be achieved by 2030 thus helping India fast-track action towards the achievement of both nationally determined contributions and sustainable development goals.

Keeping this in mind, the chapter delves into the approaches for addressing non-carbon dioxide pollutants in India through the discussion of cross-cutting themes and integrated approaches. It emphasizes the importance of overarching strategies that influence multiple sectors, such as food security, climate resilience, equity, and sustainable development to reduce non-$CO_2$ emissions from different sectors in India. By exploring key themes like technology, innovation and governance, the chapter highlights how these elements can work in synergy to enhance overall climate and developmental benefits. Ultimately, this chapter advocates for regular monitoring, multi-stakeholder collaboration, market-based mechanisms and knowledge sharing to promote inclusive SLCP mitigation policies that address the diverse needs of all communities in India.

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## Key Themes

**Mitigation of short-lived climate pollutants is crucial for achieving India's climate and clean air goals.** With the exception of HFCs, SLCP mitigation also improves air quality by reducing surface concentrations of fine particulate matter ($PM_{2.5}$) and ozone formation. Evidence suggests that strategies that tackle the two together are up to 50% more cost-effective[38]. Yet, current policies on air pollution and climate change are formed in silos and overall action has largely focussed on decarbonization alone with a lack of emphasis on short-lived pollutants.

SLCP mitigation offers additional co-benefits in the form of improved health outcomes and food security. Globally, comprehensive mitigation measures targeting SLCPs could cut the rate of global warming in half (a 0.6°C reduction) while helping to prevent 7 million premature deaths from outdoor and household air pollution annually and preventing 52 million tonnes of crop losses annually by 2030[39]. The health benefits of SLCP mitigation are largely due to the BC measures[40], and the largest share of these benefits accrues to the source region. Improvements in refrigeration energy efficiency through HFC mitigation measures not only increases the affordability of refrigeration but also reduces food waste. Mitigation of SLCPs is also linked with enhanced incomes and creation of new revenue streams[41]. In Vietnam, farmers increased their net income by approximately $137 per hectare using alternate wetting and drying techniques for rice cultivation when water subsidies were not provided.[42] Additionally, generating biogas from agricultural waste, such as manure, offers a cost-effective source of clean energy and creates new local revenue opportunities[43].

**Tackling these pollutants is vital for advancing action on Sustainable Development Goals.** Mitigation measures[44], such as clean cooking solutions for reducing black carbon emissions, help reduce household energy costs (SDG 7), free up time for income-generating activities (SDG 8), and improve educational opportunities, especially for women and children (SDG 4). By lowering air pollution and improving public health, SLCP mitigation contributes to reducing premature deaths and diseases caused by poor air quality, particularly for vulnerable populations. Methane reductions are crucial for protecting agricultural productivity by reducing ozone pollution, supporting food security and improving crop yields (SDG 2).

Mitigation measures[45] for tackling hydrofluorocarbons also support economic growth, innovation, and energy efficiency (SDG 8 and SDG 9) by promoting cleaner industrial technologies and job creation. In urban areas, SLCPs improve air quality and reduce environmental impacts (SDG 11) through better waste management (SDG 12). By reducing emissions like methane and black carbon, SLCPs help slow near-term climate change, mitigate extreme weather events, and protect ecosystems (SDG 13). Additionally, these measures promote sustainable land use and reduce deforestation (SDG 15) while contributing to responsible consumption and production (SDG 12).

Overall, these mitigation measures will not only help India achieve climate goals but also accelerate progress on key development initiatives, including the Swachh Bharat Abhiyan, PM Ujjwala Yojana, and the National Clean Air Programme. The co-benefits of these measures cut across sectors and cater to several development areas. An understanding of non-$CO_2$ mitigation in the context of these key development themes including food security, equity and justice, climate adaptation & resilience, technology & innovation and governance, is essential for the development of holistic strategies. Consideration of the overall benefits of these mitigation measures also helps offset the cost of implementing these strategies.

**Food Security:** While India has achieved self-sufficiency in basic food staples and even exports surpluses for crops like rice, it faces mounting threats to food security due to a warming climate and rising heat stress. Mitigating non-carbon dioxide pollutants like black carbon and methane offers a crucial opportunity to delay the adverse effects of global warming, reduce ozone formation, improve crop yields and avoid nutrient losses. Similarly, smart-fertilizer management limits the use of nitrous oxide and promotes sustainable soil health. HFC mitigation through modern cold chains can help reduce food losses significantly, thus enhancing access to nutritious food and helping stabilize prices, especially in food-insecure regions.

Interestingly, a UNEP global study[46] indicates that rapid implementation of 16 SLCP control measures to reduce CH4 and BC could prevent the annual loss of over 50 million metric tonnes of crop yields by 2030, with India experiencing one of the greatest benefits. This is especially crucial for rice-producing regions like Punjab and Haryana[47], where unsustainable farming practices and skewed subsidies have hindered crop diversification efforts and exacerbated groundwater depletion, thus threatening long-term agricultural sustainability.

**Equity & Justice:** Acting on short-lived climate pollutants, especially in the near-term, is critical not only for ensuring food security but also preserving the livelihood of workers and reducing the risks of premature deaths amongst the vulnerable population. Research[48] shows that providing clean cooking fuels to reduce black carbon emissions remains the most effective way to reduce premature deaths from air pollution, with low-income households expected to benefit the most. Policy incentives under the PM Ujjwala Yojana are expected to have significant positive outcomes for women and children, who disproportionately face the brunt of indoor air pollution. The agriculture sector is another key contributing sector of SLCP emissions. It is dominated by small and marginal farmers who are most vulnerable to post harvest losses. Modern cold chains with HFC-alternatives can not only help reduce food losses but also increase farmer incomes[49].

Further, ensuring a just transition for affected workforce is extremely crucial, especially given the labor-intensive nature of most contributing sectors. For instance, in the brick kiln sector, which is a key contributor of black carbon emissions, the workers are often low-income seasonal migrants who face a heightened risk from these climate mitigation efforts that promote cleaner, mechanized kilns. This is particularly true for the state of Haryana, where compliance with the National Green Tribunal's (NGT) orders[50] has meant that brick kilns are only allowed to operate four months a year resulting in huge economic losses, both for the workers and the state. This necessitates the need for targeted support and reskilling opportunities, without which these workers may struggle to transition to alternative employment in greener industries. While SLCP mitigation measures can help preserve livelihoods, concerted efforts are crucial to protect vulnerable communities from the risks associated with this transition.

**Climate Resilience & Adaptation:** Mitigating short-lived climate pollutants (SLCPs) will also help avoid tipping points and enhance local climate adaptation. For instance, reducing black carbon emissions[51] can slow glacier melt in the Himalayas, improve water security, stabilize monsoon patterns, and reduce extreme weather events like floods and droughts. Further, as the demand for cooling and refrigeration increases, HFC mitigation strategies will be crucial for adapting to rising temperatures. As the demand for cooling and refrigeration increases, appliances such as room air conditioners will transition from a luxury to a necessity and refrigerants will be crucial for avoiding food losses. Transitioning to low-GWP alternatives will not only boost energy efficiency[52] and aid in mitigation but also strengthen India's climate resilience by reducing the impact of heatwaves.

**Nature-based solutions:** Reforestation, afforestation, ecosystem restoration, and sustainable land management can also play an indirect role in tackling short-lived climate pollutants (SLCPs) by enhancing natural carbon sinks and reducing emissions. Recent research has shown that tree barks of forests can absorb methane[53], thus providing an innovative opportunity to improve methane mitigation through forestry practices. Additionally, restoring ecosystems like wetlands can mitigate methane emissions, while healthy forests reduce the need for land clearing, preventing biomass burning that releases black carbon. Sustainable land management also improves soil health, reducing the need for nitrogen fertilizers that contribute to nitrous oxide emissions.

**Governance & Policy:** Effective governance structures, policy frameworks, and institutional mechanisms will be key in facilitating coordinated and coherent action on short-lived climate pollutants. Given India's quasi-federal structure[54], subnational governments will play a crucial role in implementing these strategies as most of the key contributing sectors for these pollutants including agriculture, dairy/cattle, urban affairs, and waste fall under the jurisdiction of states. The good news is that several states have already kickstarted action on these pollutants through integrated planning, dedicated emission inventories and co-benefit assessments, including Haryana, Punjab[55], Karnataka[56], Uttar Pradesh and Madhya Pradesh. The World Bank Indo-Gangetic Plain Project[57], spread across five states in India, has provided dedicated funding support and set targets for short-lived climate reductions, including black carbon and methane, under the Regional Airshed Program.

International experience shows that coordinated efforts, actionable targets, local capacity-building, community engagement and mapping of co-benefits are crucial for effective SLCP mitigation. Going forward, the success of any governance and policy intervention will rely on political will, funding support, inter-state and inter-departmental collaboration, and robust monitoring and evaluation mechanisms.

**Technology & Innovation:** Unlike decarbonization which relies on broad structural changes in the economy, short-lived climate pollutants can be mitigated with more cost-effective technologies and end-of-pipe solutions. However, in some sectors, high initial costs of SLCP-mitigation technologies, such as electric cookstoves, advanced waste management systems, and cooling efficiency innovations, can limit their adoption. Investments in R&D can help in developing cost-effective, affordable technologies which are tailored to local contexts, thus enabling their large-scale adoption. Further, government support in the form of subsidies, tax breaks and other such incentives is essential to encourage greater private sector investments and enable large-scale deployment of these technologies. Evidence[58] suggests that demand aggregation can help solve for the high cost of mitigation technologies and help de risk investments. This is particularly true for high investment waste-to-energy technologies such as anaerobic digesters and landfill gas recovery systems. Use of blended finance instruments[59] can further derisk these investments and help scale these technologies faster and more effectively.

International Cooperation: International cooperation is essential for effectively addressing short-lived climate pollutants (SLCPs) and must adhere to the principle of common but differentiated responsibilities. The success of mitigation efforts in India largely depends on support from developed countries. Unlike in developed nations, where SLCP emissions are often linked to luxury consumption, many of these emissions in India are tied to survival, particularly methane. Insufficient international cooperation could jeopardize India's trade, economic stability, and food production[60].

Financial and technical assistance from developed nations—through research and development, technology transfer, and capacity building—is crucial for overcoming these challenges. Additionally, grace periods that allow developing countries more time to meet SLCP reduction targets, as seen in the Montreal Protocol, are vital for ensuring a just transition. A phased approach to the transition is necessary for countries like India. While mandatory reduction targets, such as those in the Global Methane Pledge, may conflict with India's national interests, swift voluntary action on SLCPs, supported by financial and technical cooperation from developed countries, can help mitigate costs of delay while yielding local co-benefits.

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## Integrated Solutions

**There is no-one size fits all approach for tackling non-$CO_2$ pollutants in India.** Different pollutants like methane, black carbon, and nitrous oxide come from varied sectors such as agriculture, transport, and waste management. Addressing these requires tailored solutions that account for India's unique local context, including rural versus urban settings, and sector-specific challenges. Effective mitigation demands cross-departmental collaboration between ministries like agriculture, environment, energy and pollution control boards to align policies, pool resources, and achieve integrated outcomes that support both climate and air quality goals.

**Improving measurement and monitoring systems and techniques for black carbon, methane and HFC emissions is crucial.** Addressing short-lived climate pollutants requires robust and cost-effective data solutions. In line with WHO's 2021 Air Quality Guidelines, improving reporting mechanisms to include the measurement of black carbon and elemental carbon within $PM_{2.5}$, alongside total $PM_{2.5}$ mass concentrations, can be extremely beneficial for targeted action[61]. Assessment of spatial hotspots of $PM_{2.5}$ can help identify primary combustion sources of black carbon. Combining traditional monitoring instruments, such as aethalometers, with portable, low-cost devices like microAeths can provide real-time emissions data at critical sources, including waste burning sites and highways. The use of this satellite data can be particularly useful for monitoring methane emissions.

## Moving towards a data-driven approach for tackling SLCPs in India

**Addressing non-carbon dioxide pollutants in India poses significant challenges, primarily due to the lack of comprehensive and current emission inventories. Many existing inventories are outdated or lack sufficient governmental support, leading to critical gaps in understanding the spatial distribution and emission sources for these pollutants. For example, the last national methane inventory was published in 2018, and there has been no coordinated government effort to create an inventory for black carbon emissions.**

**To bridge this gap, Institute for Governance and Sustainable Development (IGSD) and the Energy and Resources Institute (TERI) are closely working with subnational governments across India to produce first-of-a-kind SLCP inventories with unprecedented granularity (12x12 km grid resolution). These studies are crucial for understanding emission sources and developing targeted interventions. By modelling reduction potential of ongoing and proposed strategies, they provide pathways for quick achievement of climate and clean air goals.**

**Additionally, technological innovation and research are critical for charting an effective mitigation strategy.** Developing and scaling technologies such as low-GWP refrigerants, methane capture in agriculture, and biogas production from organic waste are essential for sustainable SLCP mitigation. India's National Mission for Enhanced Energy Efficiency and Cooling Action Plan already supports energy-efficient cooling solutions and low-GWP refrigerants. Complementing these with dedicated investments in R&D for cleaner technologies, such as waste-to-energy as in the Namakkal case study from Tamil Nadu, can further bolster SLCP reductions while promoting sustainable economic growth.

**Ultimately, market mechanisms and policy incentives will enable the adoption of the strategy at scale.** Market mechanisms, such as emission trading systems (ETS), offer targeted emissions reductions. Building on successful models like the Surat Clean Air Market[62], which reduced PM2.5 by 24%, an ETS for black carbon and other particulate matter can create economic incentives for pollution control while driving technology upgrades in industries. Additionally, adopting innovative financing models like the World Bank's Pilot Auction Facility (PAF)[63], which offers a guaranteed floor price for methane reductions, could effectively support methane and SLCP reduction from key contributing sectors.

## Moving from a single-basket to a multi-basket approach for SLCPs

**The current reliance on one-size-fits-all metrics for accounting, such as $CO_2$ equivalents, for measuring climate impacts can obscure the specific regional and temporal effects of various pollutants. These metrics treat all climate pollutants as a single currency based solely on their potential to trap heat in the atmosphere, which in turn poses the risk of oversimplifying complex dynamics[64].**

**A more effective strategy would be to adopt a "multi-basket" approach that distinguishes between long-lived pollutants, such as $CO_2$, and short-lived ones like black carbon and methane. This would create separate currencies for different pollutants, allowing for more accurate target setting and better accounting of their diverse impacts over time and space. This approach would also prevent perverse incentives in emissions trading schemes that could undermine essential $CO_2$ reductions.**

**India's planned domestic carbon market launch in 2026 presents a unique opportunity. If the country opts to trade SLCPs like methane separately from $CO_2$, it could establish a specialized market that encourages prompt action. As the world's second-largest supplier of carbon credits in voluntary markets, India could lead the way by creating a "methane-only" market. Valuing methane's global warming potential (GWP) over a 20-year period—when it is 80 times more potent than $CO_2$—could yield significantly higher returns on investment. For instance, every $1 invested in methane reduction projects could return $0.80 at the GWP20 standard, compared to only $0.20 at the GWP100 standard[65].**

**Collaborations with international partners for technology transfer, R&D, and capacity-building can further accelerate progress.** India's participation in global initiatives, like the IEA Technology Collaboration Programmes[66], can facilitate the adoption of best practices and cutting-edge technologies, supporting the transition to low-GWP refrigerants, advanced agricultural practices, and sustainable energy solutions for SLCP mitigation. Enhanced partnerships can also enable knowledge-sharing on market mechanisms, such as carbon credits, to incentivize clean technologies across sectors.

**Beyond sector-specific and pollutant-specific policies, co-control or complementary policies, such as reducing coal consumption and improving energy efficiency, can be even more effective in reducing overall GHG emissions.** Energy efficiency measures highlight the power of co-control approaches. Recent studies demonstrate that increasing the efficiency of appliances like air conditioners by 30%[67], when combined with switching to low-GWP refrigerants, could double GHG reductions compared to using low-GWP refrigerants alone. By tackling multiple pollutants together, these policies produce greater environmental and public health benefits alongside long-term climate gains

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## Sector-wise Pathways to Sustainability

While integrated strategies are necessary to get a holistic overview, sectoral strategies can help create tailored approaches, given the diverse pollutants involved—like methane, black carbon, and HFCs—and the unique mitigation opportunities available within each sector. Targeted sectoral strategies allow for more effective, context-specific interventions that can significantly reduce SLCP emissions while also delivering co-benefits, such as improved air quality, energy efficiency, and sustainable development outcomes that align with India's climate and economic priorities.

## Agriculture

India's agricultural sector must focus on reducing methane, NOx, BC, and HFCs. Improved livestock management is vital for cutting methane emissions. The National Livestock Mission promotes initiatives like green fodder production and total mixed ration feeding, which can enhance digestion efficiency.[68] Additionally, using slow-release fertilizers and nitrification inhibitors can minimize nitrogen losses and improve soil health.[69]

Precision agriculture techniques are equally essential for managing nitrous oxide emissions. The government's ₹6,000 crore initiative aims to promote precision farming through technologies like drones and soil health cards to optimize fertilizer use.[70] Tailoring inputs to specific crop needs not only reduces nitrous oxide emissions but also improves crop yields. Integrating crop rotation with legumes can enhance soil nitrogen levels while lowering the need for synthetic fertilizers.[71]

Implementing better water management techniques, such as alternate wetting and drying in rice cultivation, can reduce water usage by 30% and mitigate methane emissions by about 48%.[72] Additionally, removing rice straw from paddies after harvest limits the growth of methane-producing bacteria in flooded fields.

To address black carbon emissions from stubble burning, promoting alternative crop residue management techniques is crucial. Initiatives like Punjab's Straw Management Scheme encourage farmers to use machinery for in-situ management of crop residues instead of burning them.[73] India is also phasing down HFCs in cooling systems per the Kigali Amendment, committing to an 85% reduction by 2047.[74] To reduce its emissions from the agriculture sector, the government must encourage the use of low global warming potential (GWP) refrigerants in agricultural cooling systems, such as cold storage and transport facilities.[75]

## Waste Management

India's waste sector is a significant contributor to methane and nitrous oxide.[76] As urbanization accelerates, the management of municipal solid waste (MSW) and wastewater becomes increasingly critical. To mitigate these emissions, several targeted solutions have been implemented. The Indian government has promoted initiatives like the Swachh Bharat Mission, which encourages composting and anaerobic digestion of organic waste. Facilities using anaerobic digestion can reduce methane emissions significantly as compared to traditional landfill methods.[77]

Enhancing landfill management through techniques like daily cover, compaction, and moisture reduction can limit conditions that produce methane; using tarps to cover waste prevents rainwater intrusion, reducing moisture content and subsequent methane generation.[78] Additionally, installing landfill gas collection systems reduces and captures methane, minimizing risks associated with methane-ignited landfill fires, which produce black carbon, carbon dioxide, and particulate matter emissions.[79]

$N_2O$ is primarily released during wastewater treatment processes.[80] To address this issue effectively, upgrading wastewater treatment facilities is crucial. Modernizing plants using aerobic treatment options significantly reduces $N_2O$ emissions compared to low-oxygen environments typical in many developing nations.[81] Moreover, optimizing nutrient management practices within wastewater treatment processes minimizes nitrogen losses as $N_2O$.[82] Implementing strategies that balance the carbon-to-nitrogen ratio helps reduce harmful emissions without compromising effective treatment outcomes. By transitioning towards centralized aerobic systems common in high-income countries yet adapting them for resource-constrained settings globally, significant reductions in $N_2O$ emissions can be achieved in India's waste sector.

## Energy

As India embarks on its ambitious journey toward a sustainable energy future, transitioning to renewable energy sources and enhancing energy efficiency are pivotal strategies for mitigating SLCPs. By increasing the share of renewable energy to 50% by 2030, India can significantly reduce its reliance on fossil fuels, major contributors to methane, BC and HFC emissions.[83] The energy sector accounts for approximately 10.62% of total methane emissions[84] and 8% of total $N_2O$ emissions in India.[85]

India is transitioning from coal-fired power plants to cleaner alternatives like solar and wind energy, which reduces both methane and BC emissions. SLCP emissions in this sector are exacerbated by rising energy demand due to industrialization and urbanization. Addressing these emissions is essential for combating climate change and improving air quality.

To mitigate methane and $N_2O$ emissions, India has launched several targeted initiatives. The National Action Plan on Climate Change (NAPCC) promotes energy efficiency through the Perform, Achieve and Trade (PAT) scheme, incentivizing industries to adopt cleaner technologies.[86] Additionally, the Pradhan Mantri Ujjwala Yojana aims to provide clean cooking fuel (LPG) to over 10 crore households, reducing reliance on biomass fuels that contribute to methane and black carbon emissions while improving indoor air quality.[87] Stricter regulations on oil and gas operations can further address methane emissions from fossil fuel extraction.

## Transportation

India's transport sector is a significant contributor to $NO_x$ and BC emissions.[88] As urbanization accelerates and the demand for transportation grows, emissions from this sector have become increasingly critical to address in the context of climate change and public health. The transport sector in India accounts for approximately 12.9 per cent of India's total GHG emissions from the energy sector, and 9.7 per cent of the country's overall GHG emissions, excluding land use, land-use change and forestry (LULUCF)[89] and India's road transport sector emitted 2.6 Mt NOX in 2021, about one-third of India's total NOX emissions.[90]

To mitigate these emissions, India has implemented several targeted solutions. The National Electric Mobility Mission Plan (NEMMP) promotes electric vehicles (EVs) through incentives, reducing reliance on fossil fuels and significantly decreasing NOx and BC emissions.[91] The FAME scheme further supports this transition by providing financial incentives for EV purchases and infrastructure development.[92]

The Bharat Stage Emission Standards (BSES) regulate vehicular emissions, progressively tightening limits over the years. The introduction of Bharat Stage VI norms in 2020 marked a significant advancement in emission control, imposing stricter pollutant limits on new vehicles.[93]

Expanding and improving public transportation can further reduce the number of private vehicles on the road, thereby lowering overall emissions. Together, these initiatives form a robust framework for reducing harmful emissions in India's transport sector.

## Industrial Processes

India's industrial sector significantly contributes to BC, tropospheric ozone precursors, and HFCs.[94] The Industry sector is the second-largest contributor to black carbon emissions in India,[95] with brick production alone accounting for 7% of BC emissions in India.[96] The sector also has immense sensitivity towards tropospheric ozone concentration.[97] Additionally, HFCs, primarily used in refrigeration, air conditioning, and foam manufacturing, are rapidly growing greenhouse gases in many countries, including India.

A primary approach to reducing SLCPs in industries is the installation of control technologies such as Electrostatic Precipitators, Flue Gas Desulfurization (FGD) systems, and Selective Catalytic Reduction technology.[98] The widespread adoption of these technologies can significantly reduce emissions of particulate matter, sulfur dioxide, and nitrogen oxides, which are precursors to SLCPs.

Energy efficiency measures are also crucial for SLCP reduction. The National Mission for Enhanced Energy Efficiency (NMEEE) has successfully improved energy efficiency in industries, thereby reducing carbon footprints and emissions associated with refrigeration and air conditioning systems that use HFCs.[99] The Cooling Action Plan aims to reduce cooling demand, transition refrigerants, enhance energy efficiency, and improve technology options, potentially cutting HFC emissions by 25-30% by 2037-38 compared to business-as-usual scenarios.[100]

Integrating renewable energy into industrial processes is another key strategy for reducing SLCPs, Increased use of clean energy can lower emissions from fossil fuel combustion, including those from cooling systems reliant on HFCs. Expanding market-based mechanisms like emission trading schemes to include SLCPs could further enhance cost-effective emissions reductions. The Micro, Small & Medium Enterprises sector, which significantly contributes to industrial pollution and often employs outdated technologies, requires targeted SLCP reduction efforts. The government's ZED (Zero Defect Zero Effect) scheme promotes quality and environmental management systems in MSMEs, encouraging the adoption of low-global warming potential refrigerants.[101]

India is also advancing alternatives to HFCs through research on natural refrigerants. Some companies have begun manufacturing air conditioners using propane (R-290), a low-global warming potential refrigerant.[102] Additionally, the National Cleaner Production Centre (NCPC) advocates for cleaner production technologies aimed at reducing or eliminating HFC usage in industrial processes.[103] Collectively, these initiatives support SLCP reduction in India's industrial sector.

## Power Sector

India's power sector is a significant contributor to NOx and BC. The power sector contributes 30% of national NOx emissions in India.[104] Additionally, it has the third-highest sensitivity towards tropospheric ozone concentration, indicating its substantial role in the formation of this potent SLCP.[105] The government has mandated the installation of FGD systems in coal-fired power plants to lower sulfur dioxide ($SO^2$) emissions, which indirectly reduces the formation of secondary particulate matter. Currently FGD is being installed in 537 units in Coal based Thermal Power Plants (TPPs) across the country.[106]

To address NOx, new emission standards require plants to limit NOx emissions to 300 mg/ $Nm^3$ for those built before 2003. Subsequently, MOEF&CC has revised the NOx emission levels from 300'mg/Nm3' to 450 'mg/Nm for plants built before 2003 and 100 mg/$Nm^3$ for newer installations set up after 31st December 2016.[107] Many facilities are adopting Selective Catalytic Reduction (SCR) or Selective Non-Catalytic Reduction (SNCR) technologies; however, progress has been slow, with numerous plants seeking extensions.

Coal beneficiation is another critical measure aimed at reducing emissions from coal-fired plants. The government mandates that TPPs located 500-749 km from coal mines use coal with an ash content not exceeding 34%.[108] While this policy aims to lower particulate matter emissions, its implementation faces challenges due to limited availability of low-ash coal and high beneficiation costs.

A significant emphasis on renewable energy forms a crucial part of India's SLCP mitigation strategy. The government has set ambitious targets of 175 GW of renewable energy capacity by 2022 and 450 GW by 2030.[109] Finally, the adoption of supercritical and ultra-supercritical technologies in new TPPs enhances operational efficiency and reduces emissions. As of 2020, less than one-third of India's coal capacity is supercritical, only 1 per cent in ultra-supercritical and the rest is subcritical, whereas China and Japan have significant portions with ultra-supercritical technology, improving the share of supercritical technology in Indian TPPs will contribute further to lowering SLCP emissions in India's power sector.[110] Collectively, these integrated measures aim to significantly mitigate SLCP emissions while promoting sustainable energy practices.

## Conclusion

In conclusion, effectively mitigating short-lived climate pollutants (SLCPs) in India requires a multi-dimensional, integrated approach that aligns with the country's climate, clean air, and overall development goals. By leveraging targeted mitigation strategies across key sectors such as agriculture, waste management, energy, and transportation, India can achieve significant air quality and climate benefits in the near term. The focus on cross-cutting themes like technology innovation, data-driven monitoring, and governance reform is essential for effective SLCP reduction, allowing tailored, context-specific solutions that accommodate India's regional diversity and sectoral challenges. Moreover, international cooperation for technology transfer, financial support, and knowledge-sharing will be crucial in overcoming high initial costs and ensuring just transitions for vulnerable communities. Adopting innovative market mechanisms and a "multi-basket" accounting approach that treats SLCPs distinctly from CO— will further incentivize swift action, ultimately positioning India as a leader in global climate action. Through integrated SLCP mitigation efforts, India will not only be able to advance its Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDGs) but also foster cleaner air, enhanced food securit.

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