Unlocking Durable Carbon Removal for India's Clean Air Future

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Organisation Profiles

Carbon Removal India Alliance

The Carbon Removal India Alliance (CRIA)[1] is the only non-partisan industry coalition dedicated to catalysing and supporting the growth of a thriving durable carbon dioxide removal (CDR) sector in India. The alliance exists to accelerate the development, commercialisation, and deployment of CDR technologies in India. Most of the leading CDR players in India are CRIA members.

With India poised to deliver up to 30% of global durable CDR potential by 2050, CRIA plays a pivotal role in ensuring these solutions are not only climate-effective but also economically and socially transformative. CRIA focuses on solutions with long-term permanence - such as biochar, enhanced rock weathering, direct air capture, and BECCS - while promoting ecosystem-building, research, international collaboration, and robust policy engagement. The alliance actively works with government bodies, corporates, development banks, and rural communities to mainstream CDR in India's carbon market and development agenda.

As a professional services organisation, CRIA also advances co-benefits such as improved soil health, increased agricultural productivity, and reduced air pollution. With over 20 active members and growing momentum in both private and public sectors, CRIA is leading efforts to make India a global hub for high-integrity, scalable carbon removal solutions.

CII Clean Air Better Life

CII's National Initiative Cleaner Air - Better life[2] was incepted in November 2016 with a vision to provide cleaner air and a better quality of life to every Indian citizen. The initiative aims to support a nationwide movement to cleaning air by (1) Lending common platform to governments, businesses, communities, and change makers to improve air quality, (2) Building momentum and capacities for evidence-based action on the ground and (3) Providing industry leadership for driving cross-sectoral action on air pollution.

Cleaner Air - Better Life undertakes actionable research to support communities and decisionmakers in government and industries to assess and improve outdoor air quality. We do so by engaging local communities, policymakers, industry leaders and change-makers to design and execute solutions with participatory planning and disseminating good practices and environmentally-sound solutions for wide scale adoption. The initiative focuses on building evidence and implementing strategic initiatives with participation of local communities, authorities and industries.

[1] CRIA
Website: www.cria.earth

[2] CII Cleaner Air Better Life,
Website: https://sustainabledevelopment.in/alliances/cleaner-air-better-life/

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1. Executive Summary

Air pollution in India poses a pressing and multifaceted challenge, particularly in light of the country's rapid urbanisation and simultaneous rising energy consumption. The shift from a predominantly rural to increasingly urban society has led to the intensification of key pollution sources, including transportation, industrial activities, and open burning of waste (including agriculture biomass and municipal waste).

India's air pollution crisis continues to pose significant risks on public health, environment, and the economy. As a consequence of the environmental and health risks posed by air pollution, India's economy faces costs amounting to 3.5% of its GDP every year (CII, 2021). In addition to economy this pose significant risk on public health and living environmental. Among the various contributors to India's ambient air pollution, crop residue burning in the Indo-Gangetic Plain is a dominant seasonal source. With crop residue burning contributing heavily to spikes in particulate matter ($PM_{2.5}$) there is an urgent need for scalable interventions that address air pollution. Simultaneously, India is aiming to achieve net-zero emissions by 2070, requiring transformative strategies that not only reduce GHG emissions but also remove legacy carbon dioxide from the atmosphere.

Thus, it is vital to link air pollution and climate mitigation strategies addressing short-term air quality as well as long-term climate goals. This creates a strategic opening to explore durable carbon removal (CDR) solutions that offer air pollution co-benefits. This research report explores the role of durable carbon removal solutions – including (1) Biochar, (2) Bioenergy with Carbon Capture and Storage (BECCS), and (3) Enhanced Rock Weathering (ERW) – in tackling emissions and delivering co-benefits for India's rural economy, soil health, and environmental resilience.

The Air Pollution Challenge in India

- India's annual average fine particulate matter ($PM_{2.5}$) concentration in 2024 was 50.56 $\mu g/m^3$, over five times the WHO guideline.

- India is undergoing rapid urbanisation, shifting from a predominantly rural society, which has exacerbated pollution levels due to increased energy use, industrialisation, mechanised agriculture (leading to open biomass burning), and vehicular emissions.

- Key sources of ambient air pollution include *coal-based thermal power, industrial emissions, agricultural stubble burning & open waste burning, brick kilns & construction activities, transport and road dust, household biomass burning and diesel generators*.

- Crop residue burning in states like Haryana, Punjab, and Uttar Pradesh lead to severe seasonal air pollution. Every year, 50 million tonnes (NTPC 2022) of biomass is generated and farmers burn half of it to quickly clear fields for the next sowing cycle – releasing large amounts of harmful pollutants into the air.

- Despite policy efforts and subsidy schemes, the lack of viable alternatives, high labour costs, and short sowing windows have made residue burning a recurring and entrenched practice. Traditional mitigation strategies have shown limited success due to infrastructure, behavioural, and policy gaps.

The Solution

Waste resources such as biomass and construction dust, if redirected into durable carbon removal pathways, offer substantial air pollution avoidance potential in addition to carbon removal and co-benefits such as soil enhancement, increasing crop yields, and job creation.

Durable Carbon Removal approaches with air pollution avoidance potential in India:

1. **Biochar**
   Produced via pyrolysis of agricultural waste, biochar avoids open burning, sequesters carbon in stable form, improves soil fertility, and enhances water retention. Co-benefits include reduced $PM_{2.5}$ and Green House Gas emissions, enhanced crop yields and water retention, reduced fertiliser dependence and input costs.

2. **Enhanced Rock Weathering (ERW)**
   Accelerates the natural process of CO_2 mineralisation by applying finely crushed silicate rock (e.g., basalt) to soils that removes CO_2 from the atmosphere. In India, this process could repurpose construction and mining dust, which currently contributes to air pollution, turning a waste stream into a carbon sink.

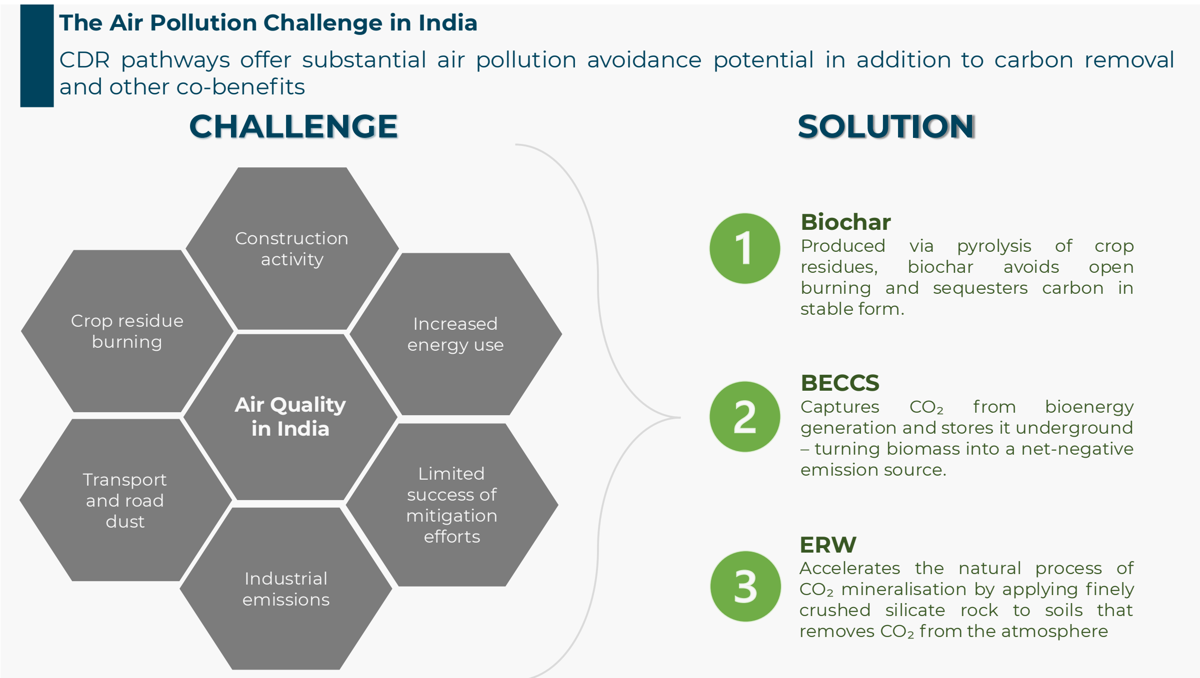
3. **Complementary Approaches**

   Bioenergy with Carbon Capture and Storage (BECCS)
   Captures CO_2 from bioenergy generation and stores it underground – turning biomass into a net-negative emission source while replacing fossil fuels.

   It is a carbon-negative technology, with potential to displace fossil fuels and reduce emissions from the power sector and industrial heat. In India, biomass-based energy is already being scaled through the National Bioenergy Programme, and BECCS can piggyback on this momentum.

   Nature-based Solutions
   Approaches like afforestation & reforestation, soil carbon sequestration, alkaline waste utilisation, blue carbon restoration, and agroforestry can also help in the mitigation of air pollution for the near- to medium-term. These methods, however, do not offer the same permanence benefits as durable CDR solutions like biochar and ERW.

CDR PATHWAYS AS A SOLUTION FOR AIR POLLUTION AVOIDANCE IN INDIA



Source: (CRIA, 2025)

Recommendations

To effectively scale durable carbon removal solutions such as biochar, bioenergy with carbon capture & storage, and enhanced rock weathering in India – as a means of addressing both air pollution and climate goals – a coordinated multi-stakeholder approach is essential.

The **Government** should integrate these durable carbon removal solutions into national programmes like the Crop Residue Management Scheme, National Clean Air Programme, Central Pollution Control Board grants and the National Bioenergy Mission. Providing financial incentives, standardised guidelines, and monitoring, reporting & verification (MRV) protocols will help mainstream adoption.

Government should also support independent scientific research and build farmer awareness on durable carbon removal, led by institutions like the Indian Council of Agricultural Research (ICAR), Krishi Vikas Kendras, and agricultural universities, through trials and practical integration to boost adoption. Investments in decentralised infrastructure – such as biomass collection hubs and pyrolysis units – will further enable scale in rural areas.

The **private sector** should lead in piloting and investing in durable carbon removal technologies, repurposing industrial and agricultural waste streams into carbon-negative products. Support for startups, development of carbon credit platforms, and financing tools such as Corporate Social Responsibility (CSR) and Environment Social Governance (ESG)-aligned investments will help drive innovation and rural engagement.

Meanwhile, **civil society** must focus on farmer awareness, field trials, and community mobilisation. Empowering local institutions like Farmer Producer Organisations and panchayats to participate in durable carbon removal will ensure wider adoption, co-benefits for soil and yield, and improved air quality.

Together, these efforts can position India as a global leader in using these durable carbon removal solutions to combat both air pollution and climate change.

SUMMARY OF RECOMMENDATIONS FOR KEY STAKEHOLDERS

Stakeholder	Recommendations
Government	Policy Integration and Financial Support
	Research and Development
	Ecosystem Development
	Incentivisation
Private Sector	Investments in durable carbon dioxide removal
	Decentralised Approach
Civil Society	Building Awareness
	Research and Demonstration Pilots
	Innovative Finance

Source: (CRIA, 2025)

Conclusion

Durable carbon removal presents a rare synergy – helping India clean its air, meet its climate targets, restore soil health, and create green rural jobs. By integrating scalable durable carbon dioxide removal solutions like biochar, bioenergy with carbon capture and storage, and enhanced rock weathering into its air pollution and agricultural strategies, India can take a leadership role in aligning near-term public health priorities with long-term sustainability goals. The need of the hour is to move from pilots to policy, from isolated projects to mainstream adoption, and from air pollution control to durable removal and transformation.

2. Defining the Problem: Pollutants, Sources, and Risks

The World Health Organisation defines air pollution as *the contamination of indoor or outdoor environment by any chemical, physical or biological agent that modifies the natural characteristics of the atmosphere*.

The U.S. Environmental Protection Agency (EPA) has identified six key air pollutants, known as *criteria pollutants*, which serve as indicators of overall air quality. These pollutants include carbon monoxide (CO), nitrogen oxides (NO and NO_2), sulphur dioxide (SO_2), ozone (O_3), particulate matter (PM), and lead (Pb) (USEPA, 2025). These pollutants, largely released from fossil fuel combustion in power plants, vehicles, and industrial activities, are responsible for both environmental degradation and a significant public health burden.

Of particular concern are airborne particulate matters like soot and dust, especially those smaller than 10 micrometres, due to their severe impact on human health. These particulates are emitted not only by urban sources but also by seasonal crop residue burning, industrial emissions, and decentralised combustion of biomass.

2.1 Sources of Air Pollution

Many major sources of air pollutants also emit carbon dioxide (CO_2), making air quality and climate challenges closely linked.

Air pollution worldwide arises from both anthropogenic and natural sources. Major human-driven contributors include the combustion of fossil fuels for transport, power generation, industry, and agricultural practices, while natural sources encompass wildfires and other ecological processes (Keswani, Akselrod, & Anenberg, 2022). These sectors contribute not only to greenhouse gas emissions but also to the release of harmful pollutants like $PM_{2.5}$, NO_x, SO_2, and CO.

Parallelly, human development influences emissions through multiple pathways. Population growth, industrialisation, and modern lifestyles drive increased emissions, while technological advancements, economic shifts, and targeted pollution control efforts work to mitigate them. The balance between these factors evolves over time. While many developed nations have successfully reduced air pollution through stringent regulation and cleaner technologies, developing countries now bear the brunt of rising pollution levels, with some experiencing the worst air quality in recorded history.

2.2 The Fallout: Health, Climate, and Economic Impacts

The presence of dangerously high levels of air pollution globally is undeniable. Air pollution poses the world's largest environmental health risk. The World Health Organisation (WHO) estimates that almost all of the global population (99%) is exposed to $PM_{2.5}$ levels exceeding the WHO guideline of 10 $\mu g/m^3$. $PM_{2.5}$, followed by PM_{10}, is strongly linked to various respiratory illnesses due to its small size, which allows it to penetrate deep into indoor spaces (Manisalidis, Stavropoulou, Stavropoulos, & Bezirtzoglou, 2020). Globally, ambient air pollution has been linked to 7 million premature deaths each year (WHO, 2024).

Beyond its severe impact on human health, air pollution also harms the natural environment. Airborne pollutants can be toxic to plants and trees, while pollutants in rainfall degrade ecosystems by depositing acid or excessive nutrients. Ground-level ozone (O_3) further exacerbates the issue, impairing agricultural crops, forests, and plant life by reducing growth rates, lowering yields, and diminishing biodiversity and ecosystem services (European Environment Agency, 2024).

The economic toll of air pollution is staggering. It leads to productivity losses, increased healthcare costs, reduced agricultural output, and damage to infrastructure from corrosive pollutants. According to the World Bank, the health damage caused by air pollution costs the global economy over USD 8 trillion annually, equivalent to 6.1% of global GDP (World Bank, 2022).

Undoubtedly, all of the above is closely linked to climate change and the consequences for humanity can be severe. Many air pollutants - including black carbon, methane, and tropospheric ozone - also act as short-lived climate pollutants (SLCPs), which have a high global warming potential. As a result, air pollution not only drives public health crises but also accelerates climate change, creating a vicious cycle where environmental degradation, agricultural decline, and human vulnerability become increasingly intertwined.

Public Health

Air pollution is the largest environmental health risk globally, contributing to a wide range of health complications. There are both short-term and long-term effects of air pollution on human health. The short-term effects are temporary and can range from mild discomfort, such as eye, nose, and throat irritation, wheezing and coughing, to respiratory conditions like asthma and bronchitis (Manisalidis, Stavropoulou, Stavropoulos, & Bezirtzoglou, 2020).

Prolonged exposure to air pollutants can worsen these health issues, posing serious risks to the neurological, reproductive, and respiratory systems. It can also contribute to the development of cancer and, in rare cases, lead to fatalities (Nakano & Otsuki, 2013). Long-term effects are more common in individuals with pre-existing health conditions.

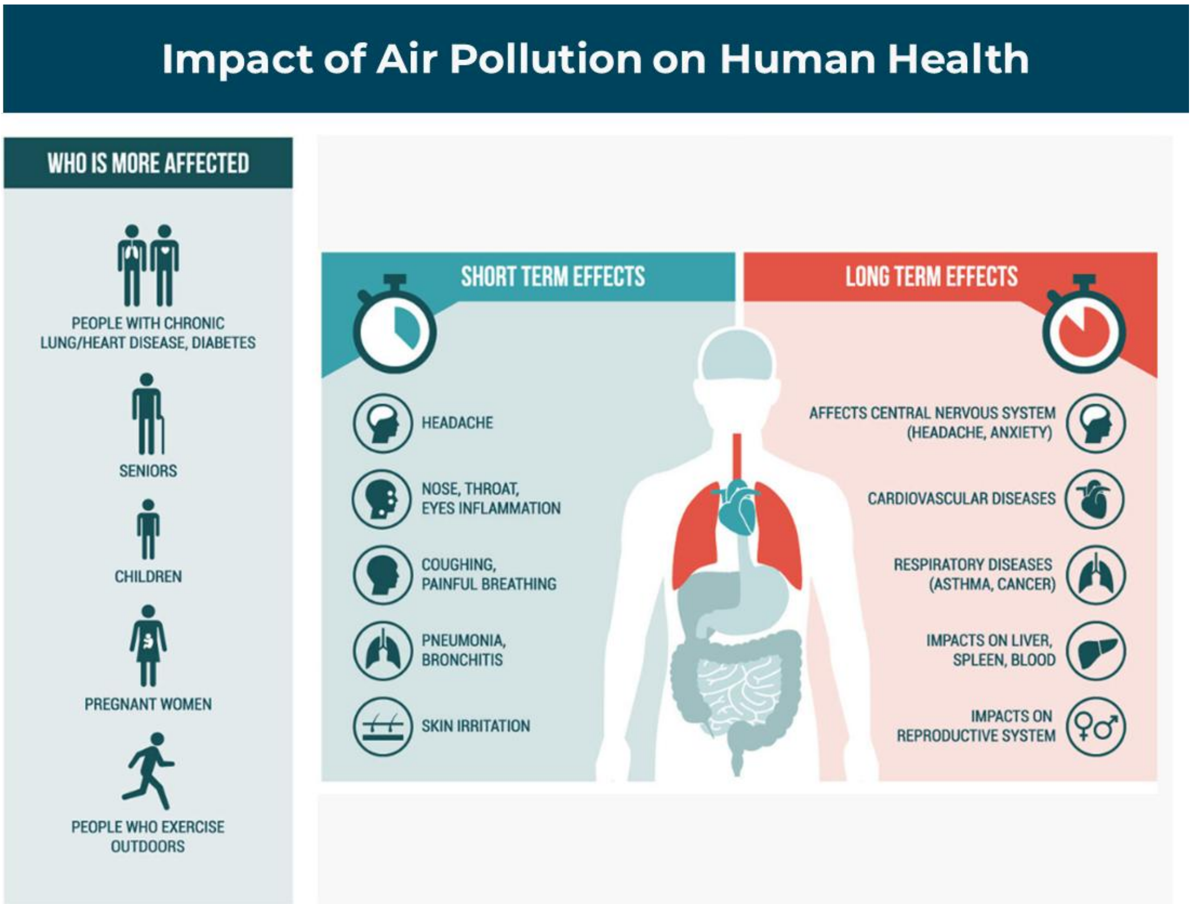


Figure 1: Effects of Air Pollution on Human Health (NDEP, 2019)

Effects on the respiratory system mainly occur due to inhalation of air pollutants like nitrogen oxides, sulphur dioxide, and ozone - these pollutants damage the respiratory tract, reduce lung function, and increase vulnerability to infections (Kampa & Castanas, 2008). Cardiovascular impacts include reduced oxygen transport, hypertension, strokes, and heart attacks (Steenhof, et al., 2014). Studies also show that prolonged exposure to air pollution affects brain health - contributing to cognitive decline, memory issues, sleep disturbances, anxiety, and developmental delays in children (Ghorani-Azam, Riahi-Zanjani, & Balali-Mood, 2016).

Neurological effects are especially concerning in children and pregnant women, with research showing associations between prenatal exposure and developmental impairments in infants (Bellinger, 2005). Pollutants can cross the placenta and affect the foetal nervous system, increasing risks of cognitive and behavioural disorders.

There is a similar trend to the health effects of air pollution in India. Exposure to dangerously high levels of $PM_{2.5}$, particularly in urban centres, has led to severe public health consequences. Negative health impacts are extremely prevalent, ranging from respiratory infections to diseases like decreased lung function, asthma, bronchitis, and chronic obstructive pulmonary diseases. The Global Burden of Disease (GBD) study attributed 1.67 million deaths in India to air pollution in 2019, including nearly 1 million from ambient air pollution (Fuller, et al., 2022).

Environment

Air pollution has far-reaching environmental consequences and contributes directly to climate change. It leads to acid rain, haze, ozone depletion, eutrophication, and damages to crops, forests, and wildlife. Acid rain, caused by sulphur and nitrogen oxides released during fossil fuel combustion, acidifies soils and water bodies, harms vegetation and aquatic life, and corrodes buildings and monuments (Wu, 2022). Eutrophication, driven by excess nitrogen and phosphorus from human activities, accelerates algal growth in water bodies, degrading fisheries and drinking water quality (Chislock, Doster, Zitomer, & Wilson, 2013). Haze results from $PM_{2.5}$ accumulation in the atmosphere, reducing visibility and harming respiratory health (Manisalidis, Stavropoulou, Stavropoulos, & Bezirtzoglou, 2020). Meanwhile, ozone layer depletion, caused by pollutants like chlorofluorocarbons and methane, increases harmful ultraviolet (UV) radiation exposure, raising risks of cancer, eye damage, and reduced crop yields (Morales-Méndez & Silva-Rodríguez, 2018).

Air pollution also disrupts ecosystems and biodiversity. It affects animal health and behaviour, weakens reproductive success, and contaminates food chains through pollutants like ammonia (Prana Air, 2021). Biodiversity plays a crucial role in ecosystem balance, and its loss can lead to disruptions in the food chain and the extinction of certain species.

Plants too suffer from reduced photosynthesis and stunted growth due to exposure to pollutants like ozone and black carbon. Short-lived climate pollutants, in particular, have been shown to suppress crop yields - it was estimated that air pollution was responsible for approximately 33% of India's wheat yield decline in 2010 (Burney & Ramanathan, 2014). Further projections suggest that by 2050, agricultural output in developing countries may decline significantly due to continued air pollution (Kunt, Köpüklü, & Güneş, 2023). These cascading effects demonstrate how air pollution is not only a health hazard but also a threat to food security, biodiversity, and climate resilience.

Economy

Air pollution imposes wide-ranging economic costs, stemming from both direct and indirect impacts. These include healthcare costs from pollution-related diseases and premature deaths, loss of productivity, damage to ecosystems, and declines in tourism and consumer activity. Poor air quality has been strongly linked with reduced workplace productivity, affecting national and global economic output (McCarthy, 2020).

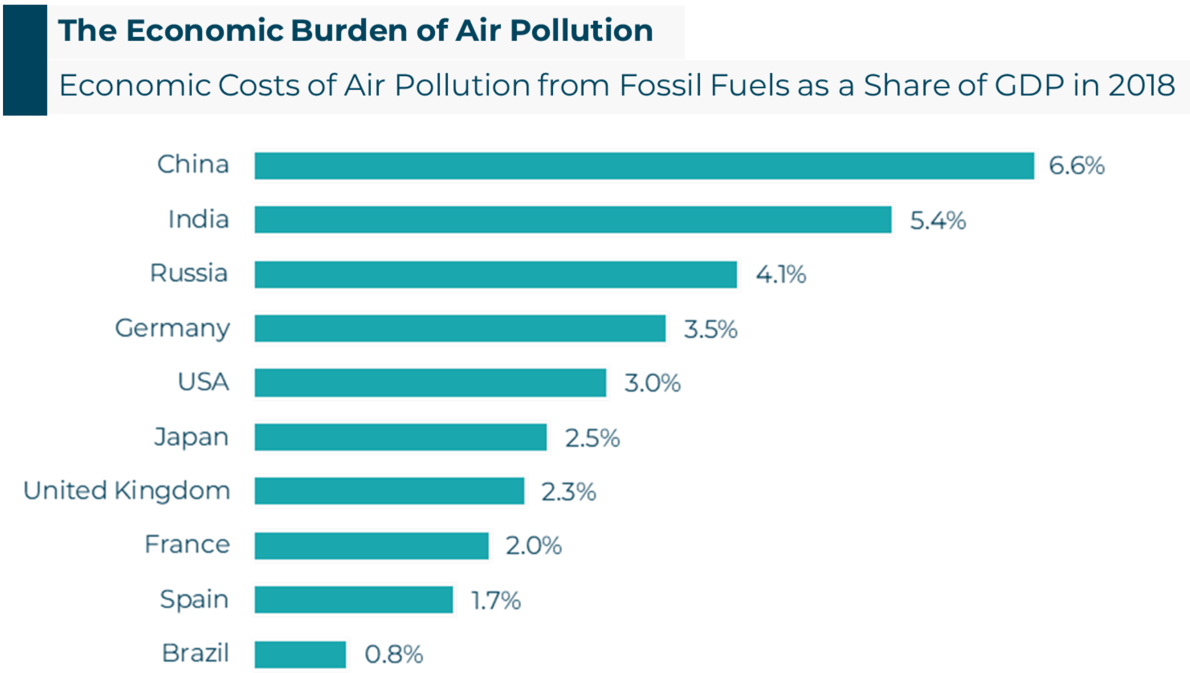


Figure 2: The Economic Burden of Air Pollution (McCarthy, 2020)

Global Economic Losses

Air pollution significantly hinders workforce efficiency and overall economic activity – resulting in the loss of 1.2 billion workdays globally each year, a figure projected to rise to 3.8 billion by 2060 (OECD, 2016). The annual welfare costs of air pollution in OECD countries alone are estimated to rise to USD 3.9 trillion by 2060, with over 90% of these losses attributed to premature deaths.

In 2018, air pollution imposed a staggering cost of USD 2.9 trillion on the global economy, equivalent to 3.3% of the world's GDP (McCarthy, 2020). The cost of the health impact of air pollution was estimated to be USD 1.4 trillion in China and USD 0.5 trillion in India in 2010 (OECD, 2016).

Economic Impact on Indian Businesses

Air pollution costs Indian businesses an estimated USD 95 billion annually, amounting to roughly 3% of the country's GDP (Gupta, et al., 2021). Although this cost has often gone unrecognised, it is both substantial and persistent. The economic impact of air pollution is felt in six key ways:

- Reduced Labour Productivity
- Decreased Consumer Footfall
- Premature Mortality
- Diminished Asset Productivity
- Rising Healthcare Expenses
- Welfare Losses

This persistent economic burden affects both national and regional economies.

GDP Loss and Regional Disparities

According to the GBD study, India experienced an economic loss of USD 28.8 billion due to lost output from premature deaths in 2019 linked to air pollution, along with an additional USD 8 billion in losses associated with pollution-related illness and morbidity (Pandey, et al., 2021). This totals to USD 36.8 billion, equivalent to 1.36% of India's GDP - more than four times the healthcare allocation in India's 2020–21 Union Budget (Kanaujia, Bhati, Lakshmanan, Nishad, & Bhattacharya, 2022).

The economic burden has affected state GDPs, ranging from 0.67% to 2.15%, with the most severe impacts seen in low per capita GDP states such as Uttar Pradesh, Bihar, Rajasthan, Madhya Pradesh, and Chhattisgarh (Pandey, et al., 2021). Among all, Delhi recorded the highest per capita economic loss at USD 62, followed by Haryana at USD 53.8.

3. India's Air Quality Crisis

India's air pollution crisis is driven by a complex interplay of natural and anthropogenic sources, leading to deteriorating air quality across both urban and rural regions. Natural factors such as mineral dust, long-range desert dust transport, and the re-suspension of soil dust within arid urban environments contribute significantly to background particulate matter levels. However, the situation is exacerbated by a range of human-induced activities.

, India continues to struggle with drastically poor air quality. Air pollution levels in Indian cities, on average, exceeding the WHO's recommended safe limit by five times(TERI, 2021) with annual average $PM_{2.5}$ levels rising to 54.4 µg/m³ in 2022..

The challenges linked to air pollution in India arise due to the complex nature of air pollutions monitoring and management from sources spread across geography. In order to develop an efficient air pollution management system, it is imperative to understand the sources of generation.

Air pollution sources can broadly be grouped into seven key sectors: transportation,

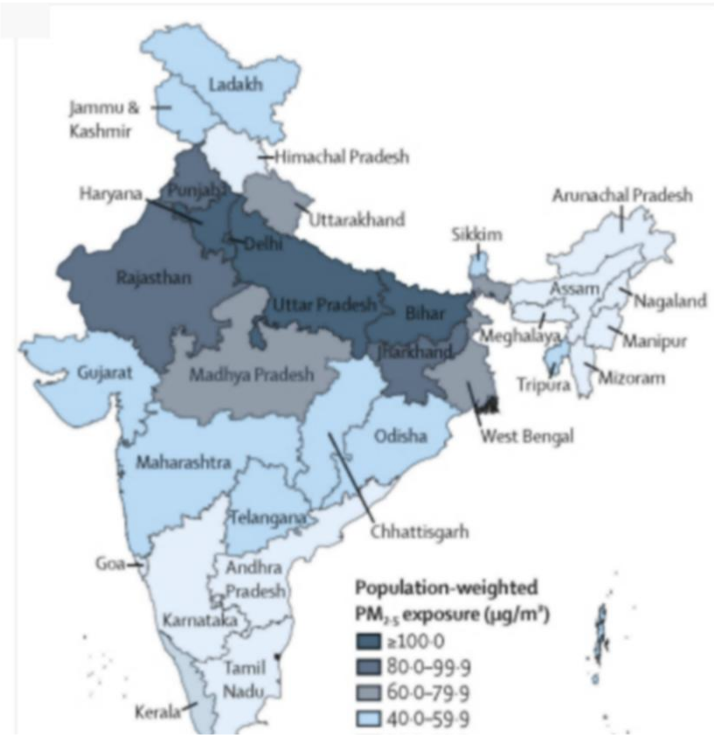


Figure 3: Exposure to air pollution in the states of India, 2019 (Pandey, et al., 2021)

industry, power generation, agriculture, waste management, biomass burning, residential, construction, and demolition activities.

Among the most critical anthropogenic sources is waste burning, particularly in the crop-residue in northern agrarian states during post-harvest seasons and burning of household & municipal waste. Residential bio-fuel combustion for cooking and heating continues to pollute both indoor and ambient air, especially in rural areas. Fossil fuel combustion in thermal power plants, emissions from agricultural activities, waste landfills, and industrial and vehicular sources are major contributors to urban air pollution. Additionally, large-scale construction activities release vast amounts of dust and particulate matter into the atmosphere (Kaur & Pandey, 2021). Various factories and manufacturing units, including cement plants and brick kilns, emit harmful air pollutants such as particulate matter, sulphur dioxide (SO_2), and nitrogen oxides (NO_x) (Balakrishnan & al, 2019).

Crop residue burning, in particular, releases vast amounts of toxic smoke - resulting in what is commonly known as crop burning pollution. Small rural industries, such as jaggery production units that rely on unprocessed biomass for energy, further add to the air pollution burden.

Transportation

Vehicles emit significant pollutants including PM2.5, nitrogen oxides, and carbon monoxide across urban centres.

Industry

Manufacturing facilities and industrial operations release harmful emissions from production processes and chemical treatments.

Power Generation

Thermal power stations contribute substantial sulphur dioxide and particulate matter to the atmosphere.

Agriculture

Crop residue burning, particularly in northern states, creates seasonal spikes in air pollution levels.

Waste Management

Open burning of municipal and electronic waste releases toxic fumes and particulates into the air.

Biomass Burning

Traditional cooking fuels and domestic biomass combustion contribute significantly to indoor and outdoor pollution.

Construction & Demolition

Building activities generate dust and debris, particularly affecting urban air quality in growing cities.

Figure 4: Major sources of air pollution in India (TERI, 2021)

Residential air pollution primarily results from the burning of solid fuels for cooking and, to some extent, heating, with common fuels including wood, dung, agricultural residues, coal, and charcoal (Arku, et al., 2018). Approximately 60% of India's population, primarily in rural areas, relies on solid fuels for cooking and heating (State of Global Air, 2024). The combustion of biomass fuels like wood, dung, and crop residues releases pollutants that not only contribute to household air pollution but also impact outdoor air quality when released into the atmosphere. Rapidly developing nations like India face the dual challenge of exposure to both ambient and household air pollution.

4. Farms on Fire: The Stubble Burning Challenge

Agricultural waste encompasses a wide range of materials, including manure and other waste from farms, poultry houses, and slaughterhouses; harvest residues; fertiliser runoff from fields; pesticides that contaminate water, air, or soil; and salts or silt drained from agricultural land (United Nations, 1997). Harvest residues – commonly referred to as crop residue – include both *field residues*, which remain in the field after harvest, and *process residues*, which are by-products from processing crops into usable products. Examples of field residues include stalks, stubble, leaves, and seed pods, while sugarcane bagasse and molasses are typical examples of process residues.

One major source of air pollution in India is crop residue burning or stubble burning. India produces between 754 million tons (Mt) of crop residues each year (Kewat & Kumar, 2022). About 228 Mt of these residues are generated as surplus biomass each year. Surplus biomass refers to the amount of crop residues that is left after all its primary uses. While crop residues serve multiple purposes – including as animal bedding, livestock feed, soil mulch, biogas generation, compost, thatching material, and fuel for domestic or industrial use – a significant portion is still burned on farms, primarily to quickly clear fields for the next planting cycle. Approximately 87Mt of surplus crop residues is burnt each year in India (TERI, 2021).

State/UT	CO_2e Emissions	State/UT	CO_2e Emissions
Andaman and Nicobar Islands	0.00	Karnataka	0.12
Andhra Pradesh	0.69	Kerala	0.00
Bihar	0.41	Lakshadweep	0.00
Chandigarh	0.00	Madhya Pradesh	9.61
Chattisgarh	0.00	Maharashtra	0.01
Dadra and Nagar Haveli	0.00	Odisha	0.00
Daman and Diu	0.00	Puducherry	0.00
Delhi	0.00	Punjab	15.12
Goa	0.00	Rajasthan	3.10
Gujarat	0.29	Tamil Nadu	0.07
Haryana	2.60	Telangana	0.22
Himachal Pradesh	0.00	Uttar Pradesh	1.34
Jammu and Kashmir	0.00	Uttarakhand	0.19
Jharkhand	0.00	West Bengal	0.05
			33.82

Table 1: State-wise CO_2e emissions (in million tons) from crop residue burning, 2020 (Deshpande, Kumar, Pillai, Krishna, & Jain, 2023)

Residue burning is most commonly practiced after the wheat harvest in April–May (pre-monsoon) and the rice harvest in October–November (post-monsoon), predominantly in northwestern India. The tight turnaround between rice harvesting and wheat sowing within the dominant rice-wheat cropping system has hindered the adoption of alternative straw management practices. As a result, crop residue burning continues to be a convenient and cost-effective method for farmers to quickly clear their fields.

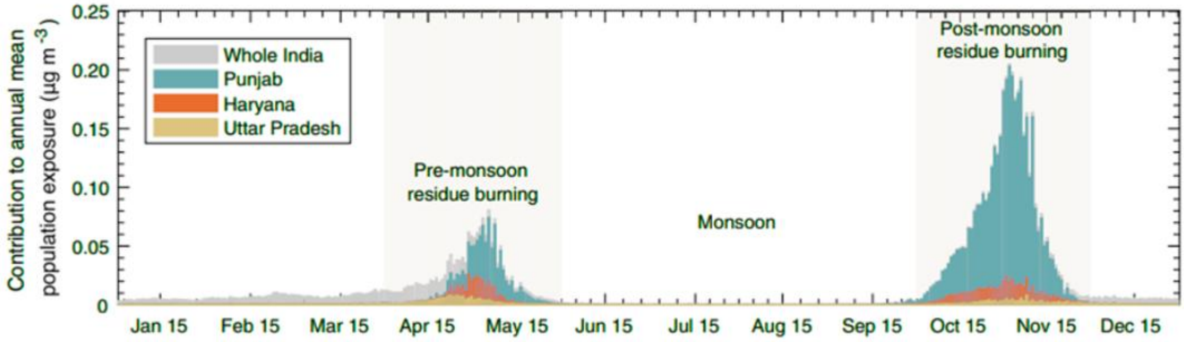
Among various crop residues, rice accounted for the largest share of residue burned at 40%, followed by wheat at 22%, sugarcane at 20%, and oilseed crops at around 5% (Jain, Bhatia,

& Pathak, 2014). The northwestern states are accountable for approximately 80% of rice and 25% of wheat residue burning (Ravindra, Singh, & Mor, 2019). Over 90% of the increase in fire-related exposure across India is attributed to agricultural fire emissions from the northwestern states – primarily Punjab, which accounts for 64%, followed by Haryana at 11%, and Uttar Pradesh at 5.7% (Lan, Eastham, Liu, Norford, & Barrett, 2022).

The issue of on-farm crop residue burning has worsened in recent years, particularly in the Indo-Gangetic Plain (IGP) region. This practice is driven by several factors, including the shortened window between harvesting and sowing, limited labour availability, high costs associated with conventional residue removal methods, and the widespread use of combine harvesters that lack straw-spreading mechanisms (TIFAC, 2018).

In today's intensive farming systems, manual labour and livestock energy can't keep pace, leading to a shift toward mechanisation like tractors and power tillers. However, manual harvesting has the advantage of removing most stubble which can be used for livestock feed or thatching, otherwise it is left to decompose or burn. The use of combine harvesters for rice harvesting worsens the issue by leaving behind 20–30 cm of stubble, making it difficult for farmers to prepare the field for the next crop.

Figure 5: India-wide annual mean population-weighted PM2.5 exposure due to crop residue burning, averaged over 2003-2019 (Lan, Eastham, Liu, Norford, & Barrett, 2022)



Burning crop residues releases substantial amounts of air pollutants such as CO_2, N_2O, CH_4, and particulate matter. For instance, burning one ton of rice straw results in the loss of approximately 5.5 kg of nitrogen, 2.3 kg of phosphorus, 25 kg of potassium, and 1.2 kg of sulphur, along with organic carbon (Ministry of Agriculture, GoI, 2014). During crop residue burning, nearly all the carbon (C), 80–90% of nitrogen, 25% of phosphorus, 20–25% of potassium, and 50% of sulphur are released into the atmosphere as various gases and particulates, contributing to air pollution. This process emits approximately 70% CO_2, 7% CO, 0.66% CH_4, and 2.1% N_2O into the air (Gatkal, et al., 2024).

In 2008–2009, the burning of 98.4 million tonnes of crop residue led to an estimated 141.15 million tons of CO_2 emissions and 1.21 million tons of particulate matter, with CO_2 accounting for 91.6% of total emissions (Jain, Bhatia, & Pathak, 2014). A study estimated that nearly 55Mt of CO_2 was released from crop residue burning in 2017-18, as compared to 8.3Mt in 1950-51 – an 85% increase (Venkatramanan, Shah, Rai, & Prasad, 2021).

When residues are left in the field or incorporated into the soil, they enrich it – particularly with organic carbon and nitrogen. Crop residue burning depletes the soil's nitrogen and carbon reserves and eliminates a significant portion of organic matter, disrupting the soil's carbon-nitrogen balance entirely (Bhuvaneshwari, Hettiarachchi, & Meegoda, 2019).

Exposure to ambient $PM_{2.5}$ from crop residue burning is linked to a three-fold increase in the risk of acute respiratory infections among the general Indian population. Global Burden of Disease's 2018 Special India Report estimated that 66,000 deaths in India were due to agricultural burning in 2015 (Lan, Eastham, Liu, Norford, & Barrett, 2022). Recent studies conducted at local, urban, and regional levels have shown that emissions from crop residue burning significantly deteriorate air quality not only within India but also across neighbouring South Asian countries like Pakistan, Nepal, and Bangladesh, as the pollutants are carried by prevailing northwesterly winds (Sarkar, Singh, & Chauhan, 2019). $PM_{2.5}$ exposure in Bangladesh, Nepal, and Pakistan due to crop residue burning in India ranges from 0.24% to 12% of the exposure levels experienced within India.

The effects of crop residue burning extend beyond human health and air pollution – it also negatively impacts economic growth and contributes to various social issues. These include reduced lower agricultural productivity, worsened socioeconomic conditions for farmers, and climate-related consequences (Singh, et al., 2022). Additionally, crop residue burning accelerates soil erosion and harms soil porosity, nutrient content, organic matter, and microbial life leading to reduced crop production and agricultural value addition to the economy. The annual loss in agricultural yield due to crop residue burning is estimated at around USD 60 million (INR 5,000 million) (Bimbraw, 2019). As a result, stubble burning not only lowers farm output but also diminishes agriculture's overall contribution to India's GDP.

Over the five years spanning 2017-22, crop residue burning in India led to an estimated economic loss of approximately USD 1.5 billion (IFPRI, 2019). Air pollution has increased operational costs and resulted in the loss of around 820,000 jobs in the tourism sector (Dey, 2021). Key industries affected include tourism, real estate, construction, insurance, and aviation. To discourage crop residue burning, some states impose monetary penalties on farmers; however, continued use of this practice has long-term effects on agricultural productivity.

The Effects of Crop Residue Burning

Crop residue burning affects soil, health, economic development, and atmosphere

Soil	Health	Economic Development	Atmosphere
• Declining microbial biomass • Loss of soil organic carbon • Declining soil fertility • Nitrogen losses	• Declining pulmonary and lung function • Increased mortality rates	• Productivity loss • Loss of farmer's income per capita	• Climate change • Smog and haze • Aerosol and particulates • Increase of toxic pollutants (e.g., CH4, CO)

Figure 6: Impacts of crop residue burning (Singh, et al., 2022)

Focused government interventions to enhance crop residue management are valuable investments. While crop burning is a common practice worldwide, in India it is predominantly concentrated in the northwest. However, over the past decade, the adoption of new harvesting technologies has led to its spread across other parts of the country.

The Ministry of Agriculture and Farmers' Welfare (MoA&FW) introduced the National Policy for Management of Crop Residue (NPMCR) in 2014 to address the issue of crop residue burning. This was followed by a ban issued by the National Green Tribunal (NGT) in 2015 on stubble burning across Rajasthan, Uttar Pradesh, Haryana, and Punjab, which aimed to curb residue burning through recycling measures and public awareness initiatives (Datta, Emmanuel, Ram, & Dhingra, 2020). Additionally, such burning is considered a punishable offence under the Air (Prevention and Control of Pollution) Act of 1981 (Kaushal, 2020).

Despite these efforts, there was a notable surge in paddy residue burning across the Indo-Gangetic Plain in 2020 (60% increase compared to last year), likely linked to the disruptions caused by the COVID-19 pandemic and lax enforcement by regulatory bodies (Ravindra, Singh, & Mor, 2022).

5. From Waste to Worth: Sustainable Solutions for Crop Residues

Crop Residue Management (CRM) practices can be divided into two categories – in-situ and ex-situ. While in-situ involves managing the residue directly in the field where the crop was harvested, ex-situ involves removing the residue from the field and using it elsewhere for production.

A balanced combination of in-situ and ex-situ crop residue management strategies, implemented through a holistic approach that offers suitable solutions, optimally leverages existing resources, and establishes efficient supply chains can significantly help curb open field burning of crop residues.

The Indian government has introduced various initiatives to tackle and reduce air pollution and has formulated several policies and regulations that could be highly effective if properly implemented.

5.1 National Level

a) National Policy for Management of Crop Residues, 2014

The National Policy for Management of Crop Residues (NPMCR) was released in 2014 by the Ministry of Agriculture and Farmers' Welfare (MoA&FW). The NPMCR has the following objectives (Ministry of Agriculture, GoI, 2014):

- Preventing environmental degradation and the loss of soil nutrients and minerals by promoting in-situ crop residue management to curb stubble burning.
- Promoting diverse applications of crop residue, including charcoal gasification, power generation, industrial raw material for bio-ethanol production, packaging material, paper/board/panel manufacturing, composting, and mushroom cultivation.
- Enhancing capacity and raising awareness about the harmful impacts of crop residue burning, along with promoting its effective use and sustainable management.
- Development and enforcement of appropriate legal, legislative, and policy measures to prevent crop residue burning.

The Central Pollution Control Board (CPCB) and the National Remote Sensing Agency (NRSA) are engaged in pilot initiatives under the NPMCR. These projects focus on enhancing farm machinery, upgrading combine harvesters for better straw collection and grain recovery, and leveraging remote sensing technologies to monitor crop residue management practices.

b) CII-NITI Aayog "Action Plan for Biomass Management" (2018)

The Action Plan for Biomass Management jointly developed by CII and NITI Aayog under the Cleaner Air Better Life. The task force outlined a comprehensive strategy to tackle crop residue burning, one of the major causes of air pollution in northern India. The report highlights the scale of surplus biomass, especially from paddy cultivation, and the resulting environmental and economic losses from open burning.

It recommends a balanced approach combining in-situ and ex-situ biomass management: encouraging practices like mulching and soil incorporation, alongside promoting biomass-based industries such as bioenergy, biochar, briquettes, and pellets.

The report calls for:

- Policy integration and financial incentives for farmers and local bodies to prevent burning.
- Infrastructure development for biomass collection, transport, and storage.
- Public–private partnerships to create markets for biomass-based products.
- Awareness and behavioural change programs among farmers.

Pilot programme "CII Crop Residue Management Programme" started in 2018 utilising this framework demonstrate that with the right machinery, training, incentives and community participation residue burning can be reduced while improving soil health and rural livelihoods. The programme reached out to 1.28 lakh farmers and 793 villages in 2024.

c) *Central Sector Scheme for Promotion of Agricultural Mechanization for In-Situ Management of Crop Residue*[3]

Taking note of the recommendation from CII-NITI taskforce, Government of India launched this Central Sector Scheme "Promotion of Agricultural Mechanization for in-Situ Management of Crop Residue" in 2018 to curb the widespread practice of crop residue burning in Punjab, Haryana, Uttar Pradesh, and Delhi a major contributor to seasonal air pollution in the Indo-Gangetic Plain.

The Scheme aims to curb stubble burning by promoting the use of farm machinery that enables residue incorporation and mulching instead of burning. The scheme provides 50% subsidy to individual farmers and 80% to farmer cooperatives/farmer groups for setting up Custom Hiring Centres to ensure access to in-situ equipment such as Happy Seeders, Straw Management Systems and rotavator. It also supports training, demonstrations, and awareness through ICAR, KVKs, and state agencies.

The scheme has helped deploy over two lakh machines and reduce burning incidents in the states, though challenges remain for marginal & small famers access to tools, short time, and the need to link in-situ management with soil and clean air benefits for sustained impact. The policy has since evolved to include ex-situ residue utilization (such as supplying straw to industries and bioenergy plants) and expanded funding under the revised guidelines (2023-24), reflecting a shift toward integrated, circular solutions for sustainable biomass management.

d) *National Bioenergy Programme*

The Ministry of New and Renewable Energy (MNRE) initiated the National Bioenergy Programme (NBP) in November 2022. This program offers Central Financial Assistance (CFA) for components linked to power generation, biogas/bio-CNG production, and briquette/pellet manufacturing. Biomass, mainly sourced from rural areas, serves as a key feedstock for these activities (Ministry of New and Renewable Energy, 2022).

The NBP has three sub-schemes:

- ***Waste to Energy Programme*** – The aim of this programme is to promote the establishment of waste-to-energy projects that generate biogas, bio-CNG, power, or syngas from urban, industrial, and agricultural waste and residues. It offers CFA to project developers and service charges to implementing and inspection agencies upon the successful commissioning of such plants.

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[3] The Promotion of Agricultural Mechanization for In-Situ Management of Crop Residue (2018) scheme is a key operational instrument of the broader Crop Residue Management (CRM) Guidelines issued by the Ministry of Agriculture & Farmers Welfare

- ***Biomass Programme*** – The programme aims to promote the establishment of biomass briquette/pellet manufacturing units and biomass-based (excluding bagasse) cogeneration projects across the country.

- ***Biogas Programme*** – This programme aims to promote the installation of biogas plants to provide clean cooking fuel, lighting, and meet thermal and small-scale power needs. The initiative contributes to reducing greenhouse gas emissions, improving sanitation, empowering women, and generating rural employment.

e) National Clean Air Programme, 2019

The National Clean Air Programme (NCAP) was launched by the Ministry of Environment, Forest and Climate Change (MoEFCC) in 2019 to improve air quality at the regional and national levels. The programme targets to achieve a 40% reduction in PM_{10} level by 2025-26 as compared to 2019-20 levels (MoEFCC, GoI, 2024).

This initiative is launched in partnership with various Ministries and States to address worsening air quality. The MoEFCC has identified several schemes and programmes that converge with the NCAP and encourages their implementation to meet the 40% PM_{10} reduction target. This includes MoA&FW's management of stubble burning by converting stubble as a 'resource' – including in-situ and ex-situ treatment of crop residues. It also includes various actions undertaken by Commission for Air Quality Improvement (CAQM) for prevention and control of paddy straw burning in the National Capital Region and Adjoining Areas.

f) Sub-Mission on Agricultural Mechanisation

The Ministry of Agriculture and Farmers' Welfare launched the Sub-Mission on Agriculture Mechanisation (SMAM) in 2014 to promote the usage of farm mechanisation and increase the ratio of farm power to cultivable unit area to 2.5kW/ha.

The mission aims to expand farm mechanisation, especially for small and marginal farmers in low-power regions. Key objectives include promoting Custom Hiring Centres (CHCs) to make equipment accessible, setting up hubs for advanced machinery, raising awareness through demonstrations and training, and ensuring equipment quality through testing and certification across designated centres.

One of the strategies to achieve these objectives is to provide financial assistance to farmers for crop-specific farm equipment, which includes Crop Residue Machinery. The Department of Agriculture, Cooperation and Farmers Welfare is implementing SMAM in all the States and the machines identified for crop residue management are also included for financial assistance under SMAM. The government, under the mission, will provide upto 50% financial assistance for equipment for crop residue management.

g) Air Prevention and Control of Pollution Act, 1981

The Air Prevention and Control of Pollution Act was enacted in 1981 and amended in 1987 for the prevent, control and abatement of air pollution in India. The Central Pollution Control Board oversees the enactment of the Act.

The Act states that the burning of any material (except for fuel), in any area, that leads to air pollution is prohibited (GoI, 1981). Burning of crop residues, therefore, is punishable under this Act.

5.2 Sub-National Level

h) Crop Residue Management Guidelines, 2024

The Government of India released operational guidelines for crop residue management in the states of Punjab, Haryana, Uttar Pradesh, Madhya Pradesh and NCT of Delhi. These crop residue management interventions will be carried out as a component under the Rashtriya Krishi Vikas Yojana (RKVY).

The guidelines aim to:

- Safeguard the environment from air pollution and prevent nutrient loss and destruction of soil microorganisms due to crop residue burning
- Encourage sustainable crop residue management through soil incorporation and by developing efficient supply chains for its utilisation using suitable mechanisation solutions.
- Raise awareness among stakeholders via demonstrations, capacity-building initiatives, and tailored information, education, and communication (IEC) strategies for effective residue management.

To meet these goals, the focus will be on promoting widely accepted in-situ management machines and ensuring optimal use of existing and newly provided equipment. A cluster-based supply chain will be set up near industries that use paddy straw, where beneficiaries will collect, densify, store, and supply it as needed.

The State Governments of Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, and the NCT of Delhi are required to submit a comprehensive Annual Action Plan covering all crop residue management interventions. Funding will be shared between the Centre and the States in a 60:40 ratio for former states, while the Centre will bear 100% of the cost for the NCT of Delhi (MoA&FW, 2024).

The interventions aim to boost in-situ paddy straw management and prevent the burning of 1.5Mt of surplus straw over three years. Around 333 biomass depots (4500Mt capacity each) will be set up across Punjab, Haryana, Uttar Pradesh, and Madhya Pradesh. This will significantly reduce air pollution, create approximately 900,000 man-days of employment, and promote a reliable supply chain for straw use in power, bio-CNG, and bio-ethanol production – encouraging fresh investment in the biomass-to-energy sector (MoA&FW, 2023).

i) National Green Tribunal Act, 2010

The National Green Tribunal (NGT), set up under the National Tribunal Act, was established for *the effective and expeditious disposal of cases relating to environmental protection and conservation of forests and other natural resources* (Ministry of Law and Justice, 2010).

In December 2015, the NGT banned crop residue burning in the states of Rajasthan, Punjab, Uttar Pradesh, Haryana, and NCT of Delhi. The Tribunal encourages in-situ practices for crop residue management and the promotion of machinery to manage residues. The NGT also mandates the imposition of environmental compensation on those who violate the ban, with the state governments responsible for collecting it.

j) Promotion of Agricultural Mechanisation for In-Situ Management of Crop Residues

Following National Green Tribunal (NGT) orders, funds were allocated under the SMAM with a 60:40 Centre-State sharing model. However, SMAM efforts were found insufficient. As a result, a dedicated Central Sector Scheme was launched in 2018–19 to support Haryana, Punjab, Uttar Pradesh, and Delhi with subsidies for in-situ crop residue management machinery.

Under this scheme, the central government will bear full cost of establishing Farm Machinery Banks or Custom Hiring Centres of crop residue management machinery; Procurement of Agriculture Machinery and Equipment for crop residue management; and Information, Education and Communication for awareness on crop residue management (MoA&FW, 2020). The scheme focuses on promoting in-situ crop residue management and establishing Farm Machinery Banks for custom hiring of crop residue machinery.

k) ***Commission for Air Quality Management in National Capital Region (NCR) and Adjoining Areas, Act 2021***

The act constituted a statutory body Commission for Air Quality Management in National Capital Region (NCR) and Adjoining Areas (CAQM). The Commission plays a pivotal role towards issuing directives / advisories, guidelines, coordination and monitoring of efforts of all the stakeholders towards abatement of air pollution in the NCR. CAQM is working towards spreading awareness regarding air pollution among various sections of society and promote awareness of the collective steps that the public may take through publication, the media, seminars and other available means.

Commission coordinates actions on monitoring of air quality with the government of Delhi and the adjoining states, which includes Punjab, Haryana, Rajasthan, and Uttar Pradesh. Enable better coordination, research, identification, and resolution of problems surrounding the air quality index and for matters connected therewith or incidental thereto.

The Commission issued framework to the concerned states for sustainable rice straw in the States. Provided action plan to support the transition towards non-burning of rice straw through adoption of measures including in-situ management, ex-situ management, and promotion of other crops complemented with effective monitoring, and IEC activities to enhance farmer awareness.

Strengthening enforcement of stubble burning / crop residue burning

- Empowered Deputy Commissioners / District Magistrates in Punjab, Haryana, Uttar Pradesh, and NCR-adjoining districts to initiate legal action under Section 14 of the CAQM Act against officials for inaction on stubble burning.
- Directed states to constitute "Parali Protection Force" at district/block levels, increase patrolling especially during late evening hours, and improve machinery procurement and planning for straw management.
- Launched revised action plans and issued fresh frameworks to eliminate crop residue burning, including in-situ and ex-situ measures, gap analyses, farm-mapping, etc.

Pollution from construction, demolition, vehicles, industries

- Stricter enforcement and monitoring of C&D sites for dust control: water sprinkling, anti-smog guns, video fencing, use of sensors, covering of construction materials, etc.

- Restricting on industrial fuel in NCR limiting the use of coal and promoting biofuel including rice straw based pellets and briquettes.
- Directions to migrate public transport and buses to cleaner modes (CNG / EV / BS-VI diesel), mandate cleaner fuel usage, restrict older polluting vehicles.

l) Guidelines for grant of one-time financial support under Environment Protection Change funds for establishment of pelletisation and torrefaction plants to promote utilisation of paddy straw, CPCB 2023

The Central Pollution Control Board (CPCB) under the Environment Protection Charge (EPC) funds has launched a grant scheme to promote the establishment of paddy straw–based pelletisation and torrefaction plants aimed at reducing stubble burning and promoting clean fuel alternatives. The scheme provides one-time financial support of up to ₹28 lakh/TPH for pelletisation and ₹56 lakh/TPH for torrefaction plants, limited to 40% of plant and machinery cost. Eligible units must be newly established in NCR and adjoining states and use paddy straw as feedstock. This scheme supports circular economy and clean air goals under NCAP and CAQM initiatives. While preference is given to projects started by farmer groups, Make-in-India equipment, and assured industrial off-take thus its focus is limited to fuel use in industries and TPPs.

5.3 State Action Plans

Haryana

Haryana's Department of Agriculture and Farmers' Welfare proposed an annual action plan of approximately USD 32 million (INR 268.18 crore) for 2024–25 to achieve zero paddy stubble burning during the season (Sura, 2024). An estimated 8.11 million tonnes of paddy straw will be generated, with 2.27 million metric tonnes to be used as fodder, 3.30 million tonnes managed through in-situ methods, and 2.54 million tonnes through ex-situ management, as outlined in the plan submitted under the 2024–25 crop residue management scheme.

The Haryana Cabinet has also introduced the "Haryana Ex-Situ Management of Paddy Straw Policy 2023," targeting the complete elimination of crop residue burning by 2027. The policy focuses on using paddy straw for sustainable energy, attracting private investment in straw-based projects, and strengthening connections between farmers and industries (ANI, 2023). It aims to ensure a steady supply of paddy straw to biomass projects, promoting responsible farming practices and environmentally sustainable agriculture.

The number of stubble burning incidents in Haryana fell to 2,303 in 2023, marking a 37% reduction compared to 2022 (Sura, 2024). With the State Action Plan for controlling paddy stubble burning now in effect, a significant further decline in such cases is anticipated.

Punjab

The Punjab government has set a target to manage all 19.58 million tons of paddy straw expected to be generated in 2024. According to the action plan submitted by the Punjab Pollution Control Board (PPCB), the state plans to manage the entire quantity through a combination of in-situ management, ex-situ management, and crop diversification.

Around 11.5Mt will be handled through in-situ methods using machines like happy seeders, super seeders, mulchers, and paddy straw choppers. Another 5.08Mt will be managed through ex-situ methods, while 3Mt will be addressed through crop diversification (Kumar, 2024). Under ex-situ management, 11 operational biomass power plants are already consuming 1Mt of paddy straw, along with 300,000 tons used in compressed biogas (CBG) plants. Additionally, industries are utilising about 2.07 million tons of paddy straw (Kumar, 2024).

Uttar Pradesh

The state of Uttar Pradesh is preparing to release an action plan to curb crop residue burning. A set of detailed guidelines have already been issued for the same. According to the guidelines, dedicated cells are to be established at both government and district levels for daily monitoring to prevent the burning of straw and agricultural waste (Hindustan Times, 2024).

Additionally, farmers must be educated about the negative impacts of straw burning on soil health, the climate, and human health, with strict action taken against those who continue to burn straw despite awareness efforts.

Despite efforts from the Indian government, farmers continue to burn crop residues due to lack of convenient and affordable alternatives. Eliminating crop burning will not only improve human health but will also contribute to soil and plant biodiversity and will reduce greenhouse gas emissions.

Overview of Policy Environment for Crop Residue Management in India

Governance	Governing Body	Policy	Key Objective: Overview	Key Objective: Crop Residue Management
Centre Government	Ministry of Agriculture & Farmers' Welfare	National Policy for Management of Crop Residues (NPMCR)	Preventing environmental degradation and the loss of soil nutrients and minerals by promoting in-situ crop residue management	Promoting applications of crop residues – charcoal gasification, industrial raw material for bio-ethanol production, power generation, etc.
	Ministry of New and Renewable Energy	National Bioenergy Programme (NBP)	Offering financial assistance for activities linked to power generation, biogas/bio-CNG production, and briquette/pellet manufacturing	Biomass, mainly sourced from rural areas, serves as a key feedstock for these activities
	Ministry of Environment, Forest and Climate Change	National Clean Air Programme (NCAP)	Improve air quality at the regional and national levels - 40% reduction in PM_{10} level by 2025-26 from 2019-20 levels	MoA&FW's management of stubble burning by converting stubble as a 'resource' converges with the programme
	Ministry of Agriculture & Farmers' Welfare	Sub-Mission on Agriculture Mechanisation (SMAM)	Promote the usage of farm mechanisation, especially for small and marginal farmers in low-power regions	The government will provide up to 50% financial assistance for crop residue management equipment
	Central Pollution Control Board	Air Prevention and Control of Pollution Act, 1981	Targets abatement of air pollution in India	Burning of any material (except for fuel) that leads to air pollution is prohibited and punishable
	Commission for Air Quality Management in Delhi NCR and Adjoining Area	CAQM directives / advisories	Issue directives / advisories, guidelines, coordination and monitoring of efforts of all the stakeholders towards abatement of air pollution in the NCR	Direct states to increase patrolling, improve machinery procurement and planning for straw management.
	National Green Tribunal	National Green Tribunal Act, 2010	Established the NGT for effective disposal of cases relating to environmental protection and conservation of forests and other natural resources	In December 2015, the NGT banned crop residue burning in the states of Rajasthan, Punjab, Uttar Pradesh, Haryana, and NCT of Delhi
State Government	States of Haryana, Punjab, Uttar Pradesh, Madhya Pradesh, and Delhi	Crop Residue Management Guidelines	Safeguard the environment from air pollution and prevent nutrient loss and destruction of soil microorganisms due to crop residue burning	Encourage sustainable crop residue management through soil incorporation and by developing efficient supply chains for its utilisation
	States of Haryana, Punjab, Uttar Pradesh, and Delhi	Promotion of Agricultural Mechanisation for In-Situ Management of Crop Residues	Promoting in-situ crop residue management and establishing Farm Machinery Banks for custom hiring of crop residue machinery	Central Sector Scheme launched in 2018 to provide subsidies to Haryana, Punjab, Uttar Pradesh, and Delhi for in-situ crop residue management machinery
	State of Haryana	State Action Plan	The Commission for Air Quality Management (CAQM) directed each NCR state and Punjab to prepare an action plan for controlling and eliminating crop residue burning	Haryana proposed an annual action plan of approx. $32mn for 2024–25 to achieve zero paddy stubble burning
	State of Punjab			The Punjab government targets to manage all 19.58Mt of paddy straw expected to be generated in 2024
	State of Uttar Pradesh			Uttar Pradesh is preparing an action plan to curb crop residue burning and establish dedicated cells to prevent the burning of straw and agricultural waste

Table 2: Overview of Policy Environment for Crop Residue Management in India (CRIA, 2025)

6. The Role of Durable Carbon Removal

There are various carbon removal (CDR) methods that capture and store CO_2, each differing in their level of maturity, potential impact, and durability. These methods range from nature-based solutions such as afforestation, soil carbon capture and agroforestry to engineered solutions such as biochar, enhanced rock weathering, and direct air capture (DAC).

The State of CDR categorises the two types of solutions into conventional methods and novel methods. Conventional CDR includes methods that are already deployed at scale and have a storage potential ranging a few decades; while novel CDR includes methods that are currently deployed at small scale but have a storage potential on the order of centuries to millennia (Smith, et al., 2023). Novel methods are more durable and pose a lower risk of reversal.

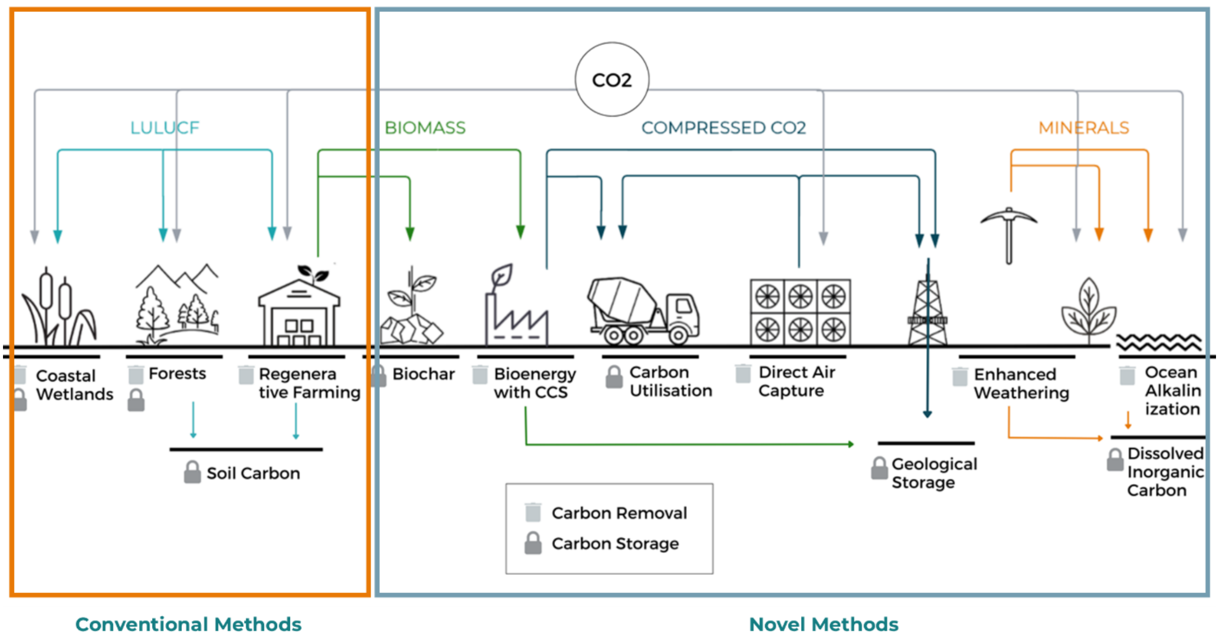

Figure 7: CDR Methods Categorised into Conventional and Novel

Currently, about 2Gt CO_2 per year is being removed, with nearly all of it coming from conventional CDR methods. Novel durable CDR approaches account for just 1.3 million tons (0.0013 Gt) annually - less than 0.1% of the total - but they are expanding at a faster rate than conventional methods (Smith, et al., 2023). In a very short span, durable carbon removal has evolved from a niche idea to a widely recognised part of climate strategies.

6.1 Durable CDR as a Pathway to Address Air Pollution

As India grapples with escalating air pollution levels, particularly from open biomass burning, durable carbon dioxide removal solutions offer a promising pathway to tackle both air quality and climate change. Unlike conventional air pollution control methods that focus solely on mitigation, durable CDR approaches such as biochar, bioenergy with carbon capture and storage (BECCS), and enhanced rock weathering (ERW) directly convert high-emission waste streams into long-term carbon sinks - simultaneously addressing pollution sources and atmospheric CO_2 levels.

As mentioned previously, open burning of crop residues results in nearly all the carbon being released into the atmosphere. While national and state governments are undertaking several measures to address this problem, there are many factors hindering the adoption of CRM practices such as cost and operation of machinery, and short period between crop cycles.

Biochar offers a tangible alternative by transforming surplus biomass - of which India produces around 178 Mt annually - into value-added products while permanently storing carbon. India ranks second globally in terms of surplus biomass availability. Its strong biomass potential positions it well to scale the technology. By diverting crop residues from open burning to biochar pathways, India can simultaneously reduce air pollution and generate durable carbon removals.

Enhanced Rock Weathering (ERW) further complements these efforts. In India, dust - primarily from construction and mining - is a major pollutant. Mining operations such as drilling, crushing, and blasting further contribute to the problem. Repurposing this dust as a feedstock for ERW not only supports carbon sequestration but also helps mitigate air pollution.

Importantly, these durable CDR methods also deliver co-benefits when applied to soil systems - improving fertility, enhancing water retention, boosting crop yields, and reducing dependence on chemical fertilisers. While nature-based approaches like afforestation and reforestation also support air quality improvements, their reversibility due to deforestation, fire, or degradation makes them less reliable in the long term.

Durable CDR thus offers India a rare opportunity to align climate action with urgent air pollution goals - by turning waste streams into solutions and building resilience into its agricultural and environmental systems.

We will explore each approach in some detail in the following sub-sections.

a) Biochar

Biochar is a charcoal-like material produced by heating biomass in the absence of oxygen through a process called pyrolysis. A wide range of biomass sources can serve as feedstock for biochar production, including agricultural crop residues, woody waste, food processing by-products, manure, and sewage sludge. The pyrolysis process converts the biomass into a stable form of carbon that can be added to soil to enhance its quality and sequester carbon for long periods.

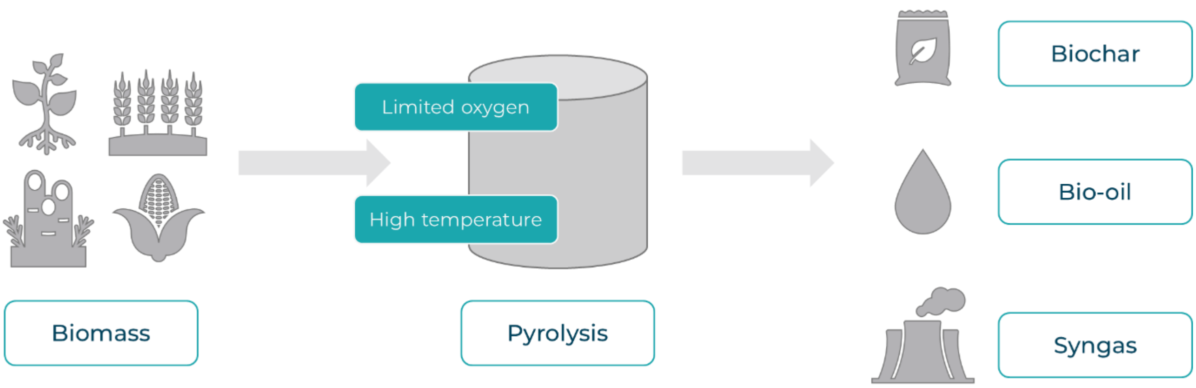

Figure 8: Biochar Production Process (CRIA, 2025)

Incorporating crop residues directly into agricultural soils can help retain nutrients and organic carbon. However, slow decomposition often creates crop management challenges. When surplus residues are left unmanaged, they can hinder land preparation, crop establishment, and early growth (Venkatesh, et al., 2018). As a result, farmers frequently resort to burning the residues, leading to environmental harm and significant nutrient loss.

In this context of India's ongoing challenge with crop residue burning, biochar offers a valuable alternative – transforming this biomass (crop residues) into a stable form of carbon storage while eliminating the need for open burning. When made from agricultural waste, biochar has the potential to sequester up to 1.2 tons of carbon per hectare per year (Yrjälä, Ramakrishnan, & Salo, 2022). CRIA's analysis shows that using just 70% of the total available surplus biomass in India can sequester 0.4Gt CO_2 per year.

Biochar is considered a highly effective method for carbon sequestration because it can remain stable in soil for centuries to millennia. It has been proposed as a means to enhance soil fertility and boost crop yields while addressing climate change. Even at early stages of adoption, biochar has shown notable environmental benefits. For instance, a study reported that applying 8 tons/ha of straw-derived biochar reduced net global warming potential by 37.8% and greenhouse gas intensity by 28.1% compared to using straw alone (Zhang, et al., 2017). With its high carbon content, stability in soil, and abundant feedstock sources, biochar offers a fast and sustainable pathway for carbon sequestration.

Additionally, biochar application in soils leads to reductions in nitrous oxide (N_2O) and methane (CH_4) emissions – the most important greenhouse gases after CO_2 and major air pollutants. Two microbial processes, namely, nitrification and denitrification, are responsible for N_2O production in soil. Biochar can affect the denitrifying microorganisms, resulting in mitigation of N_2O emissions by catalysing N_2O reduction to benign N_2 gas. It can lower nitrous oxide emissions from agricultural soils by improving soil pH, reducing compaction, and boosting microbial activity. A meta-analysis found that biochar application reduced N_2O emissions by an average of 26% (Shakoor, et al., 2021).

Incorporating biochar into manure composting has proven highly effective in reducing methane emissions from dairy operations. A 2022 study found that composting manure with biochar cut methane emissions by 79% compared to composting without it. However, livestock isn't the only agricultural source of methane – as one of the world's most widely grown crops, rice is typically cultivated in flooded fields, which create ideal conditions for methane-producing bacteria.

Rice farming accounts for around 12% of global methane emissions and about 1.5% of total global greenhouse gas emissions. Biochar has also shown potential in mitigating methane emissions from rice cultivation. An analysis by (Lee, et al., 2023) reported a significant 22.9% decrease in CH_4 emissions and 40.5% increase in soil organic carbon (SOC) after biochar application on paddy fields. Another study found that a combination of biochar and chemical fertilisers reduced CH_4 emissions by 37.4% (Somboon, et al., 2024).

Biochar was added to green roofs to study the effect of biochar amendment on improving the air quality (Hu & Chen, 2022). Their hypothesis stated that adding biochar into the green roof substrate is a potential method to purify air pollution. Simulation test results indicate that green roofs treated with biochar are significantly more effective at reducing air pollution. They showed reductions of 7.3-28.8% in CO_2, 10.6–20.7% in CO, 9.8–21.6% in SO_2, and 2.1–11.5% in NO_2. These biochar-treated roofs also demonstrated greater capacity to trap airborne particles, lowering $PM_{2.5}$ by 24.0–46.6%, PM_{10} by 17.3–38.4%, and improving overall AQI by 13.6–50.9%.

Scaling Biochar to Address Air Pollution from Open Biomass Burning in India – *Insights from Punjab*

Crop residue burning remains a leading source of seasonal air pollution in northern India. The state of Punjab, which generates over 19 million tons of paddy straw annually, experiences acute spikes in $PM_{2.5}$ concentrations during the post-monsoon period due to widespread on-farm burning. Amid this challenge, biochar presents a promising solution that simultaneously avoids air pollution and supports agricultural resilience.

In April 2024, a multi-stakeholder convening co-organised by CRIA, the Nand & Jeet Khemka Foundation, and GDi Partners, brought together policymakers, industry leaders, academics, civil society, philanthropies, and investors to evaluate the potential of biochar deployment at scale. The discussions highlighted biochar's role as a durable CDR pathway with immediate co-benefits for air quality, soil health, and rural livelihoods.

Technological Readiness and Deployment

The convening showcased a diverse range of pyrolysis technologies – from low-cost, decentralised kilns suitable for smallholder use to industrial-scale systems capable of removing over 25,000 tCO_2e annually. Other models have already removed over 11,000 tCO_2e using compact, village-scale units.

Pollution Avoidance and Agronomic Benefits

Biochar enables the productive use of crop residues that would otherwise be burned, thereby significantly reducing emissions. At the convening, stakeholders reported air pollution avoidance equivalent to the burning of over 60,000 tons of biomass. Biochar application has also demonstrated up to 30% increases in crop yields, improved soil structure, water retention, and reduced reliance on synthetic fertilisers – all of which contribute to reduced agricultural emissions and environmental degradation.

Policy Recommendations

Key recommendations emerging from the Punjab pilot include:

- Inclusion of biochar in the Crop Residue Management Scheme and the GOBARDHAN programme to enable access to subsidies and financial support.
- Scientific evidence building and farmer awareness regarding biochar and its co-benefits are key.
- Development of quality standards, transparent market mechanism, and MRV protocols.
- Establishment of dedicated facilitation platforms to enable access to the carbon market space for producers.
- Integration with existing soil health and regenerative agriculture programmes to promote adoption at the farm level.
- The need for stable and fair pricing for biomass

Strategic Outlook

The Punjab case illustrates how biochar can be positioned as a climate-smart solution with both durable carbon removal potential and immediate air pollution mitigation benefits. With the right policy push, technical guidance, and market mechanisms, this model can be replicated across other residue-burning states. As India looks to reduce its short-lived climate pollutants while building a durable CDR portfolio, scaling biochar offers a rare synergy across climate, health, and rural development objectives.

b) Enhanced Rock Weathering

Enhanced Rock Weathering (ERW) is an approach that speeds up the natural weathering of rocks to capture atmospheric CO_2, storing it as stable carbonate minerals in soils or oceans. It involves spreading crushed rocks, like basalt, on agricultural land or near oceans, to react with rain and atmospheric CO_2 – converting it to carbonates that lock away carbon permanently. The natural weathering process is sped up by human intervention by increasing the surface area of rocks through crushing.

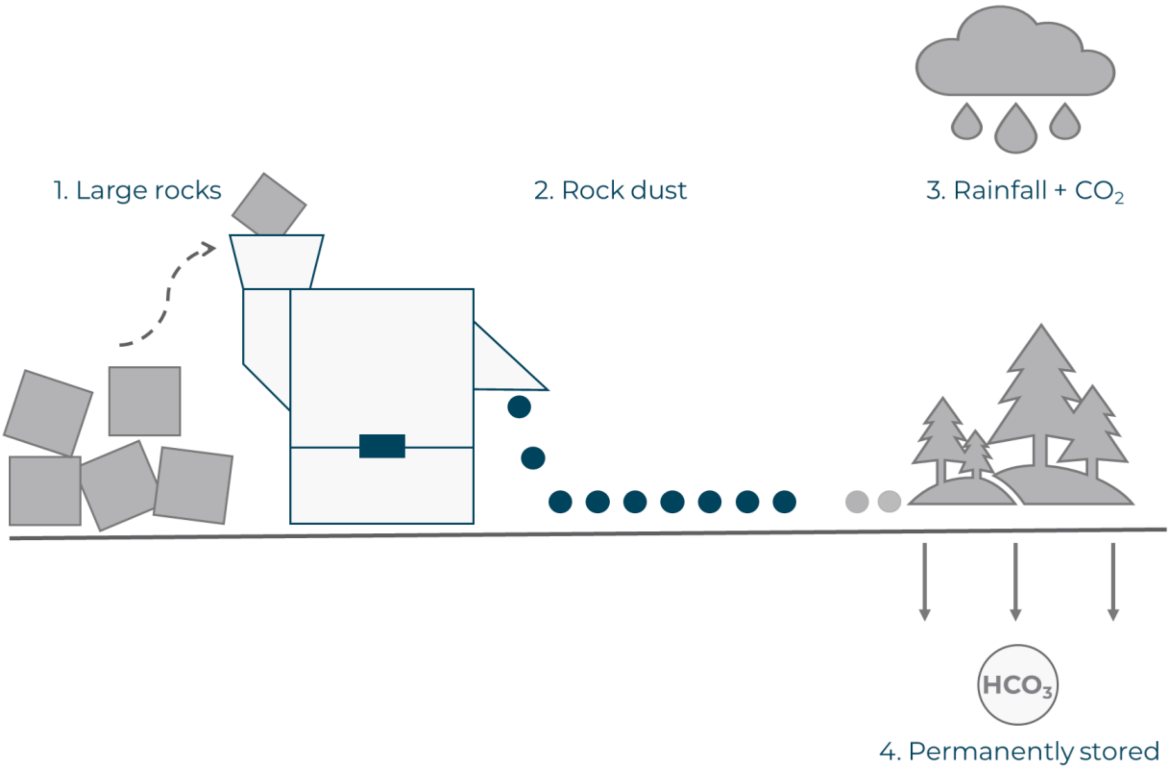

Figure 9: Enhanced Rock Weathering Process (CRIA, 2025)

Rock dust contributes to air pollution primarily through mining activities and construction, contributing primarily to higher levels of $PM_{2.5}$ and PM_{10}. Construction and resuspended road dust accounts for 8-35% of $PM_{2.5}$ contribution to ambient air across major cities of India including Delhi, Bombay, Pune, Surat and Bangalore. This dust, particularly construction dust (which is composed of silicate rocks), as well as mining dust can potentially be used in enhanced rock weathering. ERW can use this dust as feedstock, converting a pollutant into a resource. This reduces the volume of dust released into the atmosphere from stockpiles or open handling.

ERW feedstock can also include residues from mining or crushed waste rock. In major cities where air pollution is a persistent, year-round problem, this solution can help lower baseline pollution levels. ERW offers an alternative that improves soil health without generating smoke or harmful gases. ERW also increases soil pH and improves nutrient availability, reduce N_2O emissions – a potent greenhouse gas and an indirect contributor to air quality issues through ozone formation.

c) Bioenergy with Carbon Capture & Storage

While biochar and enhanced rock weathering are readily deployable durable carbon removal solutions in India, other emerging technologies like Bioenergy with Carbon

Capture and Storage (BECCS) can also play a role in the future. BECCS uses biomass to generate energy (heat, electricity, or liquid or gas fuels) while capturing and permanently storing the resulting CO_2. The biomass is transported to facilities where it is either combusted or processed to produce energy and the emitted CO_2 is then captured and stored underground to prevent it from returning to the atmosphere.

Given India's substantial surplus biomass and growing bioenergy infrastructure, BECCS has potential over the long term, especially for valorising agricultural and municipal waste. India already has a growing network of biomass processing and bioenergy plants, in addition to government support for biofuels. This creates an enabling environment for the addition of carbon capture and storage methods within the existing infrastructure. However, the technology is still in very early stages, with limited awareness and infrastructure to support large-scale deployment at present.

In parallel, the table below outlines additional methods, primarily nature-based solutions, that contribute to air pollution mitigation in India. However, these approaches carry a high risk of carbon reversal due to vulnerability to fires, disease, and land use change, and therefore do not offer the permanence associated with durable CDR methods such as biochar and ERW.

Nature-based Solutions for Air Pollution Avoidance

Solutions other than CDR also help in addressing air pollution over the short- to medium-term

CDR Method	Carbon Removal Mechanism	Air Pollution Benefits	India Relevance
Afforestation & Reforestation	CO_2 uptake through photosynthesis in trees	Traps PM2.5/PM10, absorbs SO_2/NOx, reduces heat islands	Urban greening, degraded forest restoration in states like Delhi
Soil Carbon Sequestration	Carbon stored as organic matter in soils via sustainable practices	Prevents dust pollution, improves soil structure, enhances productivity	Suitable for dryland farming regions and national soil health missions
Alkaline Waste Utilisation	Mineral carbonation using industrial by-products	Reduces dust from waste piles, avoids pollution from dumping	Large waste generation from cement and steel sectors
Blue Carbon Restoration	CO_2 stored in biomass and sediment in coastal ecosystems	Reduces coastal dust storms, stabilises sediments, improves air quality	High potential in Sundarbans, Gujarat, Odisha
Agroforestry	CO_2 absorbed by trees integrated into croplands	Controls dust, buffers wind erosion, reduces ammonia from livestock areas	Promoted under India's Agroforestry and Climate Resilient Agriculture policies

Table 3: Nature-based Solutions for Air Pollution Avoidance (CRIA, 2025)

7. Turning Ideas into Action: Recommendations for Key Stakeholders

Given the current circumstances of rising air pollution in India, with open biomass burning being one of its major sources, we recommend the following measures to scale up durable carbon dioxide removal solutions to address the issue. The recommendations are addressed towards policymakers, the private sector and civil society – a 360° approach to ensure successful implementation of the solutions.

Stakeholder	Recommendations
1. Government	a. Policy Integration and Financial Support
	b. Research and Development
	c. Ecosystem Development
	d. Incentivisation
2. Private Sector	a. Investments in durable carbon dioxide removal
	b. Decentralised Approach
3. Civil Society	a. Building Awareness
	b. Research and Demonstration Pilots
	c. Innovative Finance

Table 4: Summary of Recommendations for Key Stakeholders (CRIA, 2025)

7.1 Government

a. Policy Integration and Financial Support

I. Inclusion of Biochar and Bioenergy with Carbon Capture and Storage (BECCS) in central government schemes such as Crop Residue Management Scheme, National Clean Air Programme, Central Pollution Control Board Grant and National Bioenergy Programme.
II. Extend financial assistance for development of production facilities for durable carbon removal methods, particularly- (a) Biochar, (b) Enhanced Rock Weathering (ERW), (c) Biochar and Bioenergy with Carbon Capture & Storage (BECCS) under clean energy, sustainable agriculture, and waste management.
III. Recognition of these relevant durable carbon removal methods under the Carbon Credit Trading Scheme (CCTS) developed by Bureau of Energy Efficiency for offset mechanism

b. Research and Development

I. Support independent scientific evidence building and farmer awareness regarding co-benefits of various durable carbon removal (CDR) methods.
II. Institutions like Indian Council on Agricultural Research (ICAR), Krishi Vikas Kendra (KVKs), and agricultural universities can lead the way through leading trials and incorporating findings into farmer practices.
III. Dedicated research and field evidence development for enhanced Rock weathering and bioenergy with carbon capture and storage solutions.

c. Ecosystem Development

I. Develop clear standards and operative guidelines for field application, monitoring, reporting and verification protocols, and certification methods for durable carbon dioxide removal activities.
II. Develop a national-level digital platform/support desk to help project developers access carbon markets and generate high-integrity credits from durable carbon dioxide removal activities with dual benefit of clean air and climate mitigation

d. Incentivisation

I. Offer carbon incentives to states that incorporate durable carbon removal pathways to address open biomass burning.
II. Incentivise biochar and enhanced rock weathering application for soil enrichment under regenerative agriculture programs.

7.2 Private Sector

a. Investments in durable carbon dioxide removal

I. Catalyse private investment in production units or pilot projects for biochar, bioenergy with carbon capture and storage, and enhanced rock weathering through corporate social responsibility (CSR) funding or blended finance models.
II. Support startups and micro, small and medium enterprises working on localised and scalable durable carbon dioxide removal models, leveraging CSR and Environment, Social and Governance (ESG)-aligned capital to derisk early-stage innovations.

b. Decentralised Approach

I. Ensure the farmer communities are at the centre of innovations in biochar/bioenergy with carbon capture & storage and production, as well as financing through carbon markets.
II. Support dissemination of compact and low-cost pyrolysis systems (biochar) for smallholder farmers; and/or repurpose surplus biomass as input for bioenergy with carbon capture and storage and biochar, and rock dust from mining or construction activities for enhanced rock weathering – unlocking value from waste streams
III. Showcase durable carbon removal value proposition through learnings from pilots and research evidence improving awareness of relevant stakeholders, building trust and demonstrating tangible benefits.

7.3 Civil Society

a. Building Awareness

I. Conduct targeted awareness on the benefits of durable carbon dioxide removal approaches on soil properties, crop yields, and local communities – specifically in the Indian agro-climatic conditions.
II. Build regional consortia of civil society organisations, project developers, farmer producer organisations (FPOs), and academic institutions to drive this durable carbon dioxide removal narrative and create bottom-up demand.

b. Research and Demonstration Pilots

I. Promote farmer-led field trials and knowledge-sharing platforms for continuous refinement of durable carbon dioxide removal field application and products.
II. Encourage research on the co-benefits of durable carbon dioxide removal approaches – including agronomic, health and climate improvements.
III. Building knowledge, trust and empowerment of farmer groups, panchayats and local groups to promote adoption at the grassroots level.

c. Innovative Finance

I. Innovative financial tools with collaboration from the public, private and philanthropic sectors are essential to attract investments in durable carbon dioxide removal .
II. Opportunity for Corporates to utilise corporate social responsibility (CSR) funds to improve durable carbon removal's relevance to sustainable agriculture, clean air, climate change, and potential for carbon removal

These recommendations collectively outline a pathway for scaling durable carbon dioxide removal approaches like biochar, bioenergy with carbon capture and storage, and enhanced rock weathering as tools for air pollution avoidance, while simultaneously delivering climate, soil, and rural development co-benefits across India. By positioning these methods as viable alternatives to open biomass burning, India can accelerate its air pollution mitigation efforts while building a robust portfolio of long-term climate solutions.

8. Seizing the Durable Carbon Removal Opportunity for India

India's as a growing economic powerhouse is struggle with air pollution – especially from open biomass burning which poses a profound challenge to public health, environment, and economy. As this paper outlines, crop residue burning contributes significantly to seasonal spikes in air pollution especially in the Indo-Gangetic Plain region, leading to health deterioration, soil degradation, and productivity losses. Current mitigation efforts, though commendable, have not yet delivered transformative change due to behavioural, infrastructural and policy-level constraints.

Against this backdrop, durable carbon dioxide removal solutions such as biochar, enhanced rock weathering and bioenergy with carbon capture & storage offer a unique and timely opportunity to simultaneously address air pollution and climate change. These methods convert high-emission waste streams – like agricultural residues, organic waste, and rock/construction dust – into productive, low-carbon alternatives. They help eliminate the practice of burning biomass, absorb atmospheric CO_2, and deliver agronomic benefits like improved soil health and higher crop yields.

India is well-positioned to lead in the deployment of durable carbon dioxide removal solutions. It has vast surplus biomass, expanding renewable energy infrastructure, a strong research and innovation base, and a supportive policy environment through programs like the National Bioenergy Programme, Crop Residue Management scheme, and National Clean Air Programme. The case study from Punjab further illustrates the potential to drive both carbon removal and air pollution avoidance when supported by policy integration, technology adoption, and farmer-level awareness.

However, for these solutions to scale meaningfully, cross-sectoral collaboration is essential. The government must focus on durable carbon dioxide removal methods into existing schemes and support them through relevant levers including carbon markets, central/state subsidies, and necessary standards and guidelines. The private sector has a role to play to derisk early-stage innovation, investing in pilot projects and turning waste streams into carbon-negative resources. Civil society, meanwhile, is key to building awareness, trust, and capacity at the grassroots level – especially among smallholder farmers.

Ultimately, durable carbon dioxide removal methods offer a rare synergy: they are not just tools for carbon sequestration but also vehicles for rural development, soil restoration, and public health improvement. By embracing these technologies as part of a national strategy for air pollution avoidance and climate mitigation, India can secure cleaner air for its people today – while building climate resilience for future generation.

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