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Innovative Approaches for Sustainable Crop Residue Management

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Preface

Crop residue management has emerged as one of the major challenges for agriculture, environmental sustainability, and public health in India, especially within the rice-wheat system of India. The rising production of crop residues, combined with limited sowing window and structural limitations in farming practices, has resulted in extensive residue burning. This practice leads to significant air pollution, depletion of essential plant nutrients, greenhouse gas emissions, and decline in soil health. Concurrently, these residues represent a considerable untapped resource in the context of circular bio-economy.

Acknowledging the critical nature of both the issues and the potential they offer, the Policy Paper on *“Innovative Approaches for Sustainable Crop Residue Management”* consolidates scientific research, practical experiences from the field, policy measures, and technological advancements to outline a thorough strategy for the future. It provides critical analysis of both in-situ and ex-situ residue management strategies, assesses governmental actions, and emphasizes the importance of mechanization, integration of renewable energy, carbon markets, & institutional collaboration in achieving enduring sustainability.

This Policy Paper highlights the substantial progress made through the collaborative efforts of central & state governments, research organizations, extension services, and farming communities. The notable reduction in residue burning incidents in different areas illustrates that enhancing awareness, access to technology, financial incentives, and regulatory frameworks can collectively lead to widespread behavioural change. Nevertheless, disparities among the states and the limited development of ex-situ value chains reveal the necessity for improved policy coherence, better supply-chain infrastructure, and tailored regional strategies. Further, this document advocates for a balanced and evidence-driven approach, emphasizing in-situ residue recycling to enhance soil health & conserve resources, while also reinforcing economically viable ex-situ pathways.

I appreciate the efforts made by the Convener (Dr. Rajbir Singh), Co-convener (Dr. H.S. Sidhu), Reviewers (Dr. Yadvinder Singh & Dr. V.K. Singh) and Editors (Dr. R.K. Jain & Dr. R.K. Pal) in bringing out this document in the present form.

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(M.L. Jat)
President, NAAS

Innovative Approaches for Sustainable Crop Residue Management

1. BACKGROUND

Crop residue management (CRM) plays a crucial role in promoting agricultural sustainability, safeguarding the environment, and enhancing rural livelihoods in India. The country produces around 683 million tonnes (Mt) of crop residues each year, of which nearly 178 Mt remains as surplus biomass. Rice (33%) and wheat (21%) together account for nearly half of the total residue, while sugarcane (17%) and cotton (10%) also contribute substantial share (Jain *et al*., 2018). In the north-western Indo-Gangetic Plains, particularly in Punjab, Haryana, and western Uttar Pradesh, rice-wheat cropping system generates nearly 28.4 Mt of paddy straw annually, with Punjab accounting for more than 17 Mt of non-basmati straw (Korav *et al*., 2022). Despite its potential as a resource, approximately 43% of rice residue in India is burnt in-situ due to limited alternatives, narrow sowing windows, and operational challenges. The short three-week period between the mechanical harvesting of rice and the sowing of succeeding crop enforces farmers to open-field residue burning for quick field clearance. This practice significantly contributes to seasonal air pollution episodes during November and December throughout North India and the National Capital Territory (NCT) of Delhi, while also exacerbating greenhouse gas (GHG) emissions, soil degradation, nutrient depletion, and public health issues. Further, residue burning has been a persistent issue not only in north India, but also in the states of Madhya Pradesh, Bihar, and West Bengal leading to extensive environmental pollution.

Recognizing the urgency, the Academy had earlier released a Policy Brief in 2017 advocating large-scale promotion of CRM in north-western India (NAAS, 2017). This facilitated Government of India (GoI) support through a dedicated budget allocation of ₹1,151.80 crores to promote mechanized in-situ residue management solutions in 2018. Interventions included subsidies for CRM machinery, enabling direct drilling of wheat into standing stubble or evenly spread straw mulch, thereby eliminating the need for burning. Among available options, in-situ residue management through mulching or incorporation offers multiple agronomic and environmental advantages. Retention of residues improves soil organic carbon, enhances microbial activity, moderates soil temperature, conserves moisture, suppresses weeds, and improves nutrient cycling.

Long-term adoption has demonstrated economic benefits through reduced input costs, improved input-use efficiency, and stable or increased crop yields. Notably, Punjab and Haryana have reported substantial reduction in fire incidents in recent years, with some districts witnessing a 70-90% decline in 2025 compared to earlier baseline years, reflecting the positive impact of mechanization support and awareness campaigns. However, certain operational gaps still persist. For instance, absence or inadequate use of the Super Straw Management System (Super SMS) on combine harvesters results in uneven straw distribution, hindering efficient operation of direct seeding machinery and affecting crop establishment. Ensuring universal adoption of SMS-enabled harvesters remains critical for scaling sustainable in-situ management.

While in-situ management remains the most ecologically beneficial approach, ex-situ utilization of surplus residues presents significant opportunities under a circular bioeconomy framework. Paddy straw can serve as feedstock for bioenergy, second-generation biofuels, compressed biogas (CBG), biochar, compost, packaging materials, and other value-added products. Adoption of circular economy principles can transform agricultural residues from an environmental liability into an economic asset. Circular economy strategies (including construction, food/agriculture, and mobility) could potentially generate annual economic benefits of ₹40.4 lakh crore (USD 624 billion) for India by 2050, while reducing GHG emissions by 44% and creating economic, environmental & social value for its businesses & population (https://www.weforum.org/stories/2016/12/is-indias-future-circular).

Therefore, region-specific innovations, strengthened policy support, financial incentives, custom hiring centres (CHCs), digital monitoring of fire events, and convergence across agriculture, energy, & environment sectors are imperative. Integrating in-situ and viable ex-situ solutions duly supported by robust extension systems and market linkages will be the key to fostering a resilient, climate-smart, and resource-efficient agricultural system. This Policy Paper highlights the comparative advantages of in-situ and ex-situ residue management approaches, reviews government initiatives & current CRM status, and proposes strategic action points for scaling sustainable CRM practices across India.

2. IMPACT OF CROP RESIDUE BURNING

Crop residue burning, though often considered a quick, economical, and time-efficient method for clearing fields, has serious environmental, health, agronomic, and economic consequences. Burning of loose straw & stubble releases large quantities of greenhouse gases & air pollutants, significantly contributing to air quality deterioration, global warming and climate change. Burning one tonne of paddy straw emits approximately 1,460 kg CO_2, 60 kg CO, 3 kg particulate matter (PM), 2 kg SO_2, and nearly 199 kg ash into the atmosphere. The fine particulate matter remains suspended for extended periods and can travel long distances, driving severe smog episodes across North India and NCT, particularly during October-November. Black carbon emitted from residue burning further intensifies atmospheric warming, and is the second most important contributor to global warming after CO_2. Large-scale burning in neighbouring states also severely degrades air quality in Delhi, periodically forcing the authorities to declare air pollution emergencies in past years. At the national level, the on-field burning of approximately 92 Mt of crop residue annually results in substantial emissions of air pollutants., These include 141 Mt CO_2, 8.57 Mt CO, 0.23 Mt NO_x, 0.12 Mt NH_3, 1.46 Mt non-methane volatile organic compounds, 0.65 Mt non-methane hydrocarbons, and 1.21 Mt PM, thereby significantly aggravating air pollution and climate change impacts (Bhattacharyya *et al.*, 2021).

Elevated pollution levels of these emissions are associated with respiratory infections, chronic obstructive pulmonary disease, bronchitis, pulmonary tuberculosis, reduced pulmonary function, cardiovascular complications, eye irritation, skin disorders, and aggravated asthma, with children and the elderly being particularly vulnerable. Beyond atmospheric impacts, residue burning results in substantial losses of essential soil nutrients such as nitrogen, phosphorus, potassium, and sulfur, along with organic matter, leading to decline in soil organic carbon, microbial activity, biodiversity, and long-term soil fertility. On annual basis, rice residue burning in NW India led to a total loss of 9.2 Mt of C equivalent per year and 1.4×10^5 t of N loss. Repeated burning reduces total nitrogen and potentially mineralisable nitrogen, weakens soil structure, and increases dependence on external fertilizer inputs, thereby undermining agro-ecosystem sustainability (Kaur *et al.*, 2022). Economically, residue burning causes per-hectare losses estimated at US$118.81 due to nutrient depletion, irrigation inefficiencies, reduced yields, lower market value of produce, and health-related costs, translating into aggregate annual losses of approximately US$0.43 billion across Punjab, Haryana, and western Uttar Pradesh. In rural Punjab alone, medical expenditures and productivity losses from missed workdays have been valued at over US$1 million, reflecting the broader social cost of this practice. Thus, while crop residue burning may provide short-term convenience, its cumulative environmental degradation, public health burden, soil fertility decline, and economic losses far outweigh its immediate benefits, posing serious challenges to long-term agricultural sustainability and regional well-being.

3. GOVERNMENTAL INTERVENTIONS TO PREVENT CROP RESIDUE BURNING

Stubble burning continues to be a significant environmental and agrarian challenge across northern India, particularly in Punjab, Haryana and Uttar Pradesh, and is also prevalent in Madhya Pradesh, Bihar and West Bengal. Recognizing the seriousness of the issue, the Ministry of Agriculture and Farmers Welfare launched the National Policy for Management of Crop Residues in 2014 to promote in-situ CRM technologies, strengthen extension services, and enhance awareness among farmers. Subsequently, the Sub-Mission on Agricultural Mechanization was expanded to include financial assistance for CRM machinery, enabling both individual farmers (50% assistance) and CHCs (80% assistance) to access subsidized equipment. The Policy for CRM (2023–24) further strengthened targeted interventions in high-burden states, including NCT of Delhi, by promoting both in-situ incorporation and mulching, as well as ex-situ utilization of straw for bioenergy, ethanol production, power generation, composting and industrial uses.

In addition to technological promotion, regulatory and legal measures have been enforced to curb open-field burning. The National Green Tribunal banned crop residue burning in 2015 and authorized penalties for violations. Environmental laws such as the Air (Prevention and Control of Pollution) Act, 1981 and the Environment (Protection) Act, 1986 provide the statutory framework to address pollution caused by stubble burning. On the recommendation of NITI Aayog, emphasis was placed on machinery-based scalable solutions and strengthening incentive-linked compliance mechanisms. Governments at both central and state levels are implementing a “Push, Pull and Enforcement” strategy that combines subsidies and incentives promoting in-situ and ex-situ residue management (push), incentivising utilisation through machinery support, bioenergy, and industrial use (pull), and strict monitoring and penal action (enforcement). Environmental compensation is imposed in several states, with penalties for violations typically ranging from ₹2,500 for small landholdings to ₹15,000 for larger areas per incident, along with FIRs and real-time satellite monitoring. While punitive measures alone proved insufficient due to farmers’ financial constraints, the integrated approach focusing on technological access, financial support, awareness generation and market linkage offers a more sustainable pathway toward eliminating crop residue burning in India.

The Central Sector Scheme on Agricultural Mechanization, launched in 2018 with a total financial outlay of over ₹3,700 crore for the period 2018–2025 (Table 1), significantly strengthened the adoption of farm mechanization for CRM. The Scheme supported the distribution of more than 3.50 lakh agricultural machines including key implements such as Happy Seeders, Rotavators, Super SMS, Zero-Till Seed Drills, mulchers, straw balers, and other residue management equipment (Table 2). In addition, about 43,415 CHCs have been established to improve access to costly machinery for small and marginal farmers (Table 2). By promoting shared access through CHCs and providing substantial financial assistance, the Scheme enhanced the scalability, affordability, and timely availability of mechanized solutions, thereby contributing to reduced stubble burning and improved on-farm residue management practices.

Table 1: Funds released under the Central Sector Scheme on Agricultural Mechanization during 2018–19 to 2024–25 (₹ Crore)

Year	Punjab	Haryana	Uttar Pradesh	NCT of Delhi	ICAR	Total
2018-19	269.38	137.84	148.60	0.00	28.51	584.33
2019-20	273.80	192.06	105.28	4.52	18.48	594.14
2020-21	272.50	170.00	120.20	0.00	8.00	570.70
2021-22	331.94	193.35	159.59	0.00	6.02	690.90
2022-23	278.83	223.46	180.00	1.53	14.18	698.00
2023-24	105.00	90.00	0.00	0.00	6.99	201.99
2024-25	225.00	75.00	75.00	0.00	11.10	386.10
Total	**1756.45**	**1081.71**	**788.67**	**6.05**	**93.28**	**3726.16**

Source: Department of Agriculture & Farmers' Welfare, Ministry of Agriculture & Farmers' Welfare, GoI, 2025

Table 2: State-wise distribution of CRM machinery and establishment of CHCs during 2018-19 to 2024-25

	Punjab	Haryana	Uttar Pradesh	NCT of Delhi	Madhya Pradesh	Total
CRM Machines (No.)	160296	110550	76135	247	2849	350077
Custom Hiring Centres (No.)	27175	6794	9446	-	-	43415

Source: Department of Agriculture & Farmers' Welfare, Ministry of Agriculture & Farmers' Welfare, GoI, 2025

The trend in crop residue burning across major northern and central Indian states during 2020-2025 reflects both substantial progress and emerging regional shifts. Punjab, historically the epicentre of stubble burning, recorded a sharp and sustained decline in fire incidents from 83,002 in 2020 to 5,114 in 2025, exhibiting an overall reduction of nearly 94% (CREAMS. 2025) (Table 3). Similarly, Haryana achieved an approximate 84% reduction over

Table 3: State-wise trends in crop residue burning incidents (2020–2025)

State	Year-wise residue burning incidents (No.)					
	2020	2021	2022	2023	2024	2025
Punjab	83002	71304	49922	36663	10909	5114
Haryana	4202	6987	3661	2303	1406	662
Uttar Pradesh	4631	4242	3017	3996	6142	7290
Delhi	9	4	10	5	13	5
Rajasthan	1756	1350	1268	1775	2772	2890
Madhya Pradesh	14148	8160	11737	12580	16360	17067

Source: https://creams.iari.res.in

the same period, reporting only 662 incidents in 2025. These consistent downward trends indicate the positive impact of intensified enforcement, large-scale deployment of CRM machinery, and coordinated institutional efforts. In contrast, states such as Uttar Pradesh, Madhya Pradesh, and Rajasthan show variability and, in recent years, an upward trend in fire incidents, pointing towards a geographical redistribution of the problem beyond the traditional north-western belt. This emerging pattern underscores the need for region-specific strategies, expanded mechanization support, and stronger biomass market linkages to sustain national gains and ensure long-term reduction in stubble burning.

Strengthened agricultural mechanization, expansion of CHCs, targeted financial incentives, and intensive farmer awareness campaigns promoting in-situ CRM have led to a sustained decline in residue burning incidents during the peak period (15 September –30 November). Compared to the 2020 baseline, total incidents declined by 10% in 2021, 38% in 2022, 53% in 2023, 80% in 2024, and 86% in 2025 (Fig. 1),

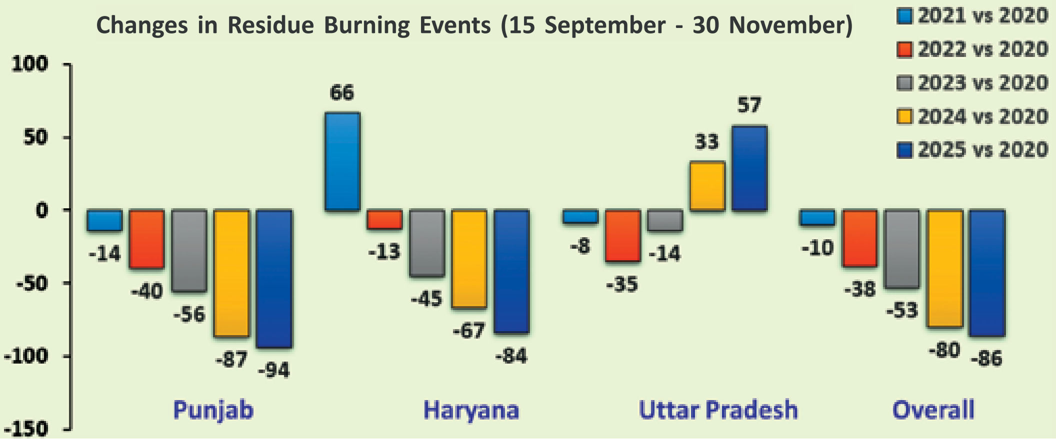

Figure 1: Per cent change in residue burning incidents across major states during 2020-2025 (https://creams.iari.res.in)

underscoring the cumulative impact of policy enforcement, large-scale machinery deployment, and behavioural change interventions over the years (Sheoran *et al*., 2026).

Although the overall number of burning incidents has declined nationally, the shifting percentage distribution highlights a geographical redistribution of residue burning incidents, signalling emerging hotspots beyond the traditional Punjab belt and underscoring the need for region-specific interventions (Fig. 2). Conversely, the relative contribution of Uttar Pradesh, Rajasthan, and particularly Madhya Pradesh increased progressively in recent years. Madhya Pradesh's share rose markedly to 43.5% in 2024 and 51.7% in 2025, emerging as the largest contributor by proportion.

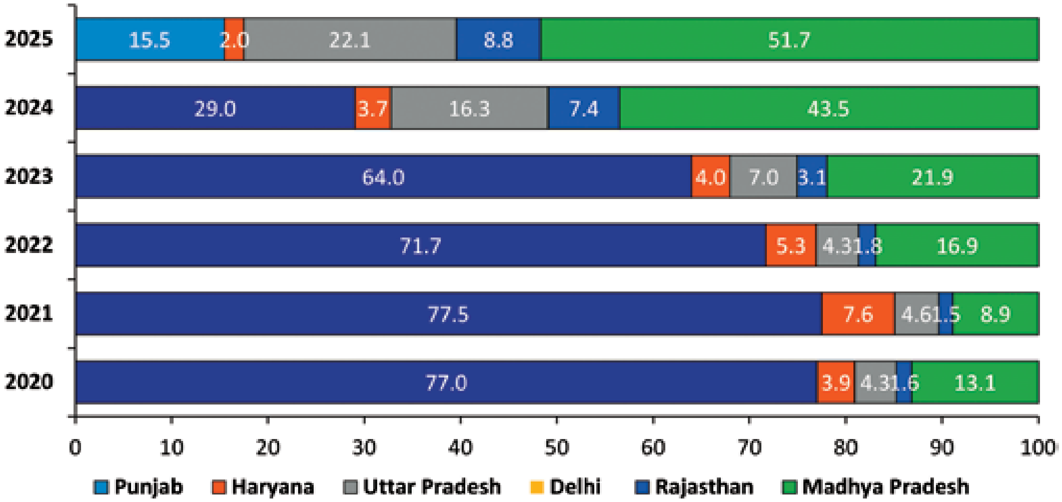

Figure 2: State-wise pattern of residue burning incidents (% of total) across major states (modified from the data collected from https://creams.iari.res.in)

During 2025-26, in-situ management of nearly 11.4 Mt of paddy straw in Punjab alone generated substantial economic and environmental returns. Reduced tillage and fuel use saved over ₹600 crore, while residue retention conserved about 571 million cubic metres of water (equivalent to one irrigation) resulting in an estimated ₹400 crore savings in electricity costs for groundwater extraction. In addition, nutrient recycling from retained straw led to fertilizer savings of nearly ₹1,681 crore at subsidized prices and about ₹2,448 crore at market rates. Collectively, the direct economic benefits far exceed the public investment made under the CRM scheme during 2018-19 to 2024-25. When extrapolated across north-western India, including Punjab, Haryana, and Uttar Pradesh, the returns on investment become even more significant, alongside long-term gains in soil health, groundwater conservation, carbon sequestration, and climate resilience.

Ex-situ CRM has been strategically positioned by GoI as a scalable, market-driven solution to eliminate open-field burning by transforming paddy straw into bioenergy, biofuels, and industrial products. Through biomass aggregation, pelletization, organized supply chains, and assured procurement systems, the government aims to convert crop residues from an environmental liability into an economic resource. Mandatory biomass co-firing (up to 10%) in coal-based thermal power plants, along with structured incentives for Bio-CNG and second-generation (2G) ethanol production, has created reliable demand for straw at remunerative prices (around ₹5,500 per metric tonne). These efforts are being advanced by the Ministry of Petroleum and Natural Gas, Ministry of New and Renewable Energy, National Thermal Power Corporation, and Central Electricity Authority under flagship initiatives such as Sustainable Alternative Towards Affordable Transportation (SATAT) and the National Bioenergy Programme (2021-26), which provide capital subsidies, viability gap funding, and long-term offtake assurances.

Bio-CNG has emerged as a financially viable pathway, with production costs of about ₹26/kg and assured procurement at around ₹46/kg, offering a competitive and cleaner alternative to fossil fuels. Significant investments in 2G bioethanol plants, biomass-based power projects, and compressed biogas facilities, particularly in Punjab and Haryana, reflect expanding industrial absorption capacity. Projects such as the Indian Oil Corporation Limited Panipat 2G Ethanol Plant, innovations from Punjab Agricultural University, and growing private-sector participation have strengthened the biomass value chain, creating substantial processing capacity. However, despite strong policy backing, ex-situ CRM remains capital-intensive and currently utilizes only a fraction of total residue generation. Strengthening straw aggregation, storage, pelletization, logistics, and financial viability mechanisms are essential to scale up ex-situ pathways and institutionalize them as a sustainable market-driven solution to completely eliminate residue burning.

4. CROP RESIDUE MANAGEMENT AND CARBON CREDITS

Sustainable CRM, especially when paired with residue retention, biochar application of biochar and other regenerative agricultural practices, holds considerable promise for increasing soil organic carbon (SOC) stocks and aiding in climate change mitigation. By curbing open burning and fostering carbon sequestration in soils, these methods lower GHG emissions, while enhancing soil fertility, water retention, and long-term productivity. Each carbon credit corresponds to one metric tonne of CO_2 removed from the atmosphere or its equivalent in other greenhouse gases (CO_2e). Engaging in carbon markets allows farmers to capitalize on climate-positive practices, generating an additional income stream alongside agronomic advantages. In India, a limited number of private organizations have ventured into the voluntary carbon market to aggregate and acquire carbon credits from farmers who are implementing regenerative agricultural practices. The current average prices for voluntary carbon credits hover around USD 2.35 per tonne of CO_2, with projections suggesting stabilization near USD 10 per tonne in the medium-term, which could potentially boost income flows at the farm level.

In January 2026, the GoI sanctioned the Aadi Project, developed by Grow Indigo under Verra-one of the foremost Voluntary Carbon Standards globally. This project is anticipated to yield over 4 Mt of CO_2-equivalent annually through emission reductions and removals, while also increasing the income of participating farmers by an estimated 7% through carbon revenue. The initiative encompasses various crops and incorporates nature-based solutions such as residue management, biochar and enhanced irrigation practices.

Nevertheless, several obstacles hinder the scalability of carbon-linked CRM initiatives. Monitoring, reporting, and verification (MRV) costs, delays in credit issuance, concerns regarding data accuracy, and methodological inconsistencies present challenges for farmers. The variability in soil types, climatic conditions, and farming practices further complicates carbon accounting. To fully leverage carbon markets, India must strengthen uniform protocols, ensure transparency, reduce transaction costs, and build institutional capacity. With growing global demand for credible carbon offsets and advances in digital monitoring technologies, India is well-positioned to emerge as a leader in agricultural carbon markets, provided environmental integrity and equitable farmer participation remain central to the framework.

5. APPROACHES FOR CROP RESIDUE MANAGEMENT

Effective CRM is a vital component of sustainable agriculture, aligning with circular economy principles. Many strategies of CRM have been developed and recommended as better alternatives to burning. These CRM strategies are broadly classified into in-situ management (retention/mulching or incorporation within the field) and ex-situ management (removal and utilization outside the field). In-situ management remains the most ecologically sustainable and immediately scalable approach for reducing residue burning in intensive rice-wheat system. However, ex-situ options involve baling & transporting residues for use as raw material in bioethanol & biofuel production, biomass-based power plants, biogas generation, paper & pulp industries, mushroom cultivation, composting, and other bioeconomy applications.

5.1. In-situ Crop Residue Management

In-situ CRM is practiced in two principal ways: (i) surface retention of straw as mulch using Happy Seeder, Smart Seeder machines; and (ii) incorporation of residues into the soil using MB plough, Super Seeder etc. In-situ technologies are environmentally sound and agronomically beneficial. Moreover, retaining residues as surface mulch improves soil organic carbon (SOC), enhances microbial activity, moderates soil temperature, conserves moisture, mitigates heat stress, suppresses weeds, and improves water use efficiency & nutrient cycling. Compared to incorporation, mulching offers additional benefits in moisture conservation, mitigation of terminal heat stress, and improved water and nitrogen use efficiency in the succeeding wheat crop (Singh and Sidhu, 2014; Jat *et al.*, 2019). Surface retention using Happy Seeder under zero tillage has been reported to increase wheat yields by 5–13% compared to conventionally sown crops (Sidhu *et al.*, 2015), while also contributing to greater carbon sequestration than straw incorporation and reduced cost of cultivation. Mechanized in-situ residue management gained strong momentum and wider farmer acceptance. The Happy Seeder and Smart Seeder (an improved variant of the Happy Seeder) enable direct drilling of wheat into standing rice stubbles. This integrated operation reduces turnaround time, lowers fuel and labour costs, conserves soil moisture, moderates soil temperature, suppresses weed emergence, and promotes sustainable conservation agriculture. The Super Seeder facilitates in-situ incorporation of anchored rice stubbles by mixing standing and loose straw into the soil through a rotary mechanism, followed by simultaneous seed and fertilizer placement in rows. Despite concerns regarding its environmental and soil health impacts, farmers increasingly prefer it due to faster seed emergence and cleaner field conditions. The use of Super SMS-equipped combine harvesters significantly enhances the efficiency of subsequent seeding operations by ensuring even distribution of straw, thereby facilitating direct drilling of wheat into residual soil moisture. This practice helps reduce biotic and abiotic stresses, including weed pressure, lodging, Karnal bunt, and termite incidence, while improving soil health and lowering GHG emissions. In Punjab, Super SMS is mandatory for registration of new combine harvesters to promote sustainable residue management.

Notably, straw incorporation requires additional tillage operations, leading to higher operational costs. However, it can be beneficial in specific cropping systems such as potato cultivation, where fine seedbed preparation is essential for optimal tuber development. Incorporation also facilitates nutrient recycling, as rice straw contains nearly 80% of K, 40% of N, and 30% of P absorbed by the crop. Nevertheless, due to its high C:N ratio and lignocellulosic nature, rice straw decomposes slowly, making timing and water management critical for effective nutrient release. Composting prior to application or converting straw into biochar through thermal processes can enhance nutrient availability and improve soil organic carbon content.

Empirical evidence highlights the substantial economic and environmental gains from in-situ CRM adoption. Adoption of CRM reportedly results in savings through reduced cultivation costs, nutrients recycling and conservation of groundwater by saving at least one irrigation. The technology also contributed to soil temperature regulation, reduced GHG emissions, and improved climate resilience. Earlier assessments by the NAAS (2017) indicated that Happy Seeder adoption could lead to fertilizer savings of 10-15% after three to four years, yield gains of 5–10%, water savings of around 15%, electricity savings of 168 kWh per hectare, labour savings of approximately 30 hours per hectare, and cost reductions of ₹450-1000 per hectare over time. Furthermore, Shyamsundar *et al*. (2019) reported that the Happy Seeder reduced PM emissions by more than 98%, GHG emissions by approximately 80% (933 kg CO_2-equivalent ha^{-1} $year^{-1}$), and groundwater withdrawals by nearly 20% (1,412 m^3 ha^{-1} $year^{-1}$) compared with conventional practices involving burning and multiple tillage operations.

Application of bio-decomposer formulations that accelerate residue breakdown into soil organic matter and plant-available nutrients, holds promise for sustainable CRM and environmental conservation; however, their effectiveness depends on appropriate moisture conditions, timely application, and complementary residue-retention practices. Wider availability of residue management machinery and standardized operational guidelines are essential to optimize its field performance.

Overall, in-situ CRM technologies provide a comprehensive solution to residue burning by improving soil health, enhancing resource-use efficiency, conserving water, reducing production costs, and mitigating environmental pollution. Strategic scaling, improved mechanization access, and context-specific advisories will be critical to maximize their long-term sustainability and impact.

5.2. Ex-situ Crop Residue Management

Ex-situ CRM comprises collecting the residue from field for various applications such as energy production (electricity, biofuel, bioethanol, & biogas), briquetting, biochar production, composting & vermicomposting, paper & cardboard making, animal feed and mushroom cultivation (Singh *et al*., 2016; Ji *et al*., 2018; CEA, 2019; Bhattacharya *et al*., 2021; Liang *et al*., 2021; Singh *et al*., 2021; Kurinji *et al*., 2024; Mohan and Kung, 2026). However, these methods are energy-intensive, and lack the requisite infrastructure support. Some technologies designed for ex-situ management need further refinements but offer positive economic and environmental benefits (Samra and Srinivasa Rao, 2021).

5.2.1. *Baling* : Rice straw is collected from combine-harvested fields through mechanized baling for ex-situ industrial utilization. Basmati straw bales can supplement fodder supply, generating additional income (Singh *et al*., 2023). The post-harvest management typically involves a stubble shaver, baler, and zero-till (ZT) drill, enabling timely wheat sowing with minimal soil disturbance. By late 2024, over 4,500 balers & rakes had been deployed across Punjab (2,183), Haryana, and Uttar Pradesh. Baling addresses issues of low bulk density; thereby improving handling, storage, and transport efficiency.

5.2.2. *Biochar* : A promising alternative to open-field burning of crop residue is the eco-friendly conversion of crop residue into biochar—a stable, carbon-rich material. Soil amendment with biochar enhances soil organic carbon (SOC), improves soil moisture, and mitigates GHG emissions through carbon sequestration. Its GHG mitigation potential is estimated at −0.94 t CO_2 eq. t^{-1} straw (Ji *et al*., 2018), with net benefits of US$183 ha^{-1} in India (Bhattacharya *et al*., 2021). Innovations such as Takachar's portable biochar unit (Mohan and Kung, 2026) enable decentralized conversion of straw into value-added carbon products (https://thebetterindia.com/environment/turning-stubble-into-biochar-takachar-vidyut-mohan-burning-alternative-farm-waste-clean-air-10941904). Biochar also improves saline soils and crop yields (Singh *et al*., 2021) and exhibits strong contaminant sorption capacity (Liang *et al*., 2021). Wider adoption requires further research, policy support, and financial incentives. However, high initial cost associated with biochar production and application is a significant barrier for many smallholder farmers.

5.2.3. *Composting and Vermicomposting* : Composting of crop residues with animal manure and locally available green biomass improves compost quality, reduces bulk density, and facilitates easier field application. The addition of effective microorganisms further enhances decomposition and nutrient enrichment. Incorporation of dry leaf litter along with green foliage also improves compost quality. Vermicomposting offers additional advantages by producing nutrient-rich compost with better economic returns and can also serve as a substrate for mushroom production as an allied enterprise.

5.2.4. *Mushroom production* : High-protein, and nutritious mushrooms can be produced using dry and mould-free straw. Farmers may harvest about 120–150 g of mushrooms from 1 kg of rice straw. In Punjab, every year 0.02 Mt straw are reportedly utilized for the production of mushrooms.

5.2.5. ***Pelleting* :** Pelletization of loose agricultural residues into high-density, uniform, and low-moisture solid fuel pellets reduces transport costs, eases handling for boilers and furnaces, and provides a sustainable renewable energy source. The calorific value of rice straw in this form ranges from 3400 to 3600 Kcal kg^{-1}. In Punjab alone, there are currently 16 operational rice straw pellet manufacturing units, which together process around 2.32 Mt rice straw annually. Estimates indicate that co-firing 10% biomass pellets in Punjab's coal-fired power stations would necessitate 1.47 Mt paddy residue each year, representing nearly 7.4% of the total rice residue produced in the region (Kurinji *et al*., 2024).

5.2.6. ***Power generation* :** Crop residues can be co-fired with coal for renewable energy generation. The Central Electricity Authority (CEA, 2019) estimates that ~0.15 Mt paddy straw could generate around 203 GW annually through co-firing. The 2022 revised biomass utilization policy under the SAMARTH initiative mandates 5–7% biomass pellet blending in coal-based thermal plants. A 12 MW rice-residue-based power plant requires about 0.1 Mt biomass annually, necessitating large storage and handling infrastructure. In addition, such biomass energy systems generate substantial quantities of ash, and its safe disposal or utilization remains a significant operational challenge. Nevertheless, such infrastructure gaps, high logistics costs, and limited supply chains constrain large-scale ex-situ deployment.

5.2.7. ***Biogas and Compressed Natural Gas* (CNG) :** Anaerobic digestion of rice straw produces biogas and bio-CNG, offering a low-emission alternative to burning. MNRE (2018) supports waste-to-energy initiatives, while the Government sanctioned ₹564.75 crore (2023–27) with up to 50% machinery subsidy for 100 CBG plants (Khanna and Jain, 2024). Biogas systems emit significantly lower GHGs than burning, and digested sludge enhances soil fertility (Satpathy and Pradhan, 2020). Bio-CNG also reduces vehicular carbon emissions, and advanced gasification technologies enable green hydrogen extraction from crop residues. The Ministry of Petroleum and Natural Gas (GoI) has allocated ₹564.75 crore to support the CBG sector by strengthening its supply chain through subsidized procurement of bio-aggregation machinery (https://bam.eil.co.in). By 2040, a total crop residue of 810 Mt can possibly produce 172 billion m^3/year of biogas in India, if a good supply chain and an effective agricultural community are in force.

5.2.8. ***Biofuel production* :** Rice straw's lignocellulosic composition makes it suitable for 2G bioethanol production, supporting energy security and reduced fossil fuel dependence. The Government has invested nearly ₹10,000 crore in 12 advanced biofuel plants, with facilities under development in Punjab and Haryana. Bioethanol from straw is considered carbon neutral (Singh *et al*., 2016) and offers estimated gains of US$664 ha^{-1} (Bhattacharya *et al*., 2021). However, high silica and ash content can reduce enzymatic efficiency and ethanol yield. Economic viability and technological optimization remain key to scaling this pathway. Notably, farming waste would generate 10-20% of electricity required in next 15 years as well as help to reduce CO_2 emission by about 27 Mt.

Ex-situ management currently utilizes less than 15% of the total rice straw generated in northern India (Kurinji and Kumar, 2021), mainly due to logistical and economic constraints. Collection, baling, transport, and storage are time-intensive and often delay sowing of the succeeding crop. Managing surplus straw in Punjab alone would require nearly 37,000 tractor-trailers per day for about 20 days during peak harvest- an impractical scale given rural infrastructure limitation. To further enable the ex-situ utilization of rice residue biomass, an intricate network of collection centres and well-regulated supply chain management is required.

Low bulk density makes long-distance transport uneconomical, while biomass power plants require high capital investment (₹4.45-6.0 crore per MW; CERC, 2019) and substantial water, adding pressure on groundwater in states like Punjab and Haryana. Lack of assured year-round biomass supply further reduces private sector viability.

Scaling up ex-situ options demands a well-organized residue value chain with aggregation centers, storage infrastructure, and efficient logistics. However, high handling costs and weak supply-chain systems remain major bottlenecks and limit the scalability of biomass-based solutions. Moreover, complete residue removal may adversely affect soil health, underscoring the need for a balanced integration of in-situ and ex-situ strategies supported by techno-economic evaluation of viable biomass utilization pathways.

No doubt, ex-situ management can supplement in-situ CRM, but never be considered as replacement solution in the long-run. The integrated approach that incorporates both in-situ and ex-situ CRM techniques that are sustainable, scalable, tailored to specific crops and regions, socially inclusive, environmentally responsible, and technically sound will ensure sustainability and farmers adoption.

6. RECOMMENDATIONS

Reducing residue burning requires a three-pronged strategy: avoidance, awareness, and adoption. Crop diversification, particularly shifting part of the rice area to alternative crops like maize, is essential to curb residue burning practices but depends on assured markets and economic incentives. Developing high-yielding rice varieties with a higher harvest index can also help reduce straw load. Advances in CRM machinery now enable timely wheat sowing and effective in-situ residue recycling through surface retention or incorporation, an energy-efficient conservation agriculture practice. Optimal use of existing machinery, along with bridging equipment gaps, remains critical for scaling in-situ management. CRM practices improve air quality, enhance soil health, and generate economic benefits. With growing farmer awareness of the environmental and soil health impacts of burning, sustained technological support and economic incentives can accelerate the transition toward eliminating residue burning. There is a need to utilize satellite-based remote sensing technologies, in collaboration with the National Remote Sensing Agency (NRSA) and the Central Pollution Control Board (CPCB), to effectively monitor CRM practices. CRM should integrate both in-situ techniques with ex-situ solutions, customized to local agro-climatic situations and farmers’ requirement. Systematic guidelines should be developed to regulate straw baling in order to maintain SOC and fertility, while enabling industrial utilization of crop residues in a sustainable manner. Farmers should be guided to trade carbon credits and incentives for adopting various CRM options. The following steps outline a comprehensive way forward:

6.1. Strengthening Technology Awareness, Access, and Adoption Framework

- Institutionalize CRM as a mission-oriented national programme through strong inter-ministerial and implementing agencies coordination under a "whole-of-government" framework to promote sustainable agriculture, improve air quality, restore soil health, promote clean energy, support climate change mitigation, and enable large-scale behavioural and technological transformation at the field level.
- Intensify mapping of stubble-burning hotspots and strengthen IEC activities, particularly in unattended and remote villages. Establish field-based precise air quality monitoring systems to track pollution levels.
- Adopt a Pan-India, crop-inclusive CRM strategy that is context-specific, aligned with diverse agro-ecological conditions, socio-economic realities, and institutional capacities. Need-based customization will enhance adaptability, practicality, and economic viability. A comprehensive national strategy should cover all major crops and residue-burning hotspots, with region-specific solutions tailored to local challenges for effective and scalable impact.
- Rationalize incentives for CRM machinery, and improve access through CHCs and local entrepreneurs, promoting service-based delivery models that support smallholders while generating rural employment.
- Establish learning platforms at strategic locations (such as KVKs/SAUs/ICAR Institutes/Regional Stations etc.) to augment on-field demonstrations showcasing the effectiveness of CRM practices on soil health and climate resilience enabling scalable, region-specific adoption.
- Develop a robust plan to maximize the potential use of machines, including rational distribution, deployment at peak harvest periods, and promotion of CHCs to provide subsidized access to smallholders.

6.2. Enforcing Regulatory Measures

- Enforce mandatory installation and operation of Super SMS on all combine harvesters through district-level guidelines.
- Strengthen field monitoring through routine inspections and ensure strict enforcement with immediate penalties for violations related to residue burning.

6.3. Enhancing Farmer Participation and Economic Viability of Ex-situ CRM

- Develop efficient biomass supply chains for collection, storage, and transport of paddy straw, with strong farmer–industry linkages to ensure assured procurement and additional income.
- Promote ex-situ utilization through DBT-linked incentives for bioenergy and value-added products (biofuels, biochar, compost), integrating farmers with 2G ethanol, biogas, and co-firing value chains.

- Regulate straw baling for industrial use with specific time windows and quantity limits without compromising over-exploitation/removal of organic matter from the fields.

6.4. Policy Interventions and Capacity Building

- Sustain policy and financial support for CRM through subsidies payment for ecosystem services, and MSP-linked incentives, aligned with outcome-based metrics (e.g., zero burning, energy efficiency), thereby accelerating adoption and offsetting additional operational costs.
- Reform CRM subsidy frameworks by enforcing strict quality standards and price regulation to prevent equipment deterioration and price inflation. Allow repeat or phased subsidies for CRM adopters to support machinery upgrades and sustain operational efficiency.
- Strengthen Cooperatives and CHCs to monitor machinery utilization, ensure trained operator availability. Adopt GPS-based traceability and deployment systems to achieve optimal use of CRM machinery and ensure timely access during critical field operations.
- Promote biomass-based value chains (bio-CNG, biofuels, pellets, biochar) through PPPs and startups; develop robust ex-situ infrastructure and supply chains, alongside carbon and renewable energy credit frameworks to enhance farmer income and sustainability.
- Leverage long-term field data (SOC, productivity, environmental outcomes) to guide policies; strengthen satellite monitoring, ICT-based extension, region-specific R&D, and inter-ministerial coordination across agriculture, energy, and climate sectors.

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