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RETHINKING CROP RESIDUE DISPOSAL IN INDIA: SUSTAINABLE ALTERNATIVES, ADOPTION BARRIERS, AND CLIMATE CHANGE IMPERATIVES

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Abstract— **Crop residue burning remains a widespread and environmentally damaging practice in Indian agriculture, particularly across the rice-wheat belt of the Indo-Gangetic Plains (IGP). Annually, India generates over 500 million tonnes of crop residues, of which nearly 127 million tonnes are surplus, and approximately 23% is burned in open fields. In 2022–23 alone, Punjab, Haryana, and Uttar Pradesh collectively generated over 54 million tonnes of paddy straw, with 7.49 million tonnes burned in Punjab and 0.75 million tonnes in Haryana, affecting more than 14.7 lakh hectares. This practice contributes up to 44% of $PM_{2.5}$ pollution in Delhi during post-harvest months and emits approximately 15–20 million tonnes of CO_2-equivalent greenhouse gases annually, undermining India's climate goals. Despite decades of awareness and policy intervention, sustainable residue management remains uneven due to socio-economic, technological, and institutional barriers. This review critically examines both prevailing and emerging alternatives to burning, such as in-situ practices (e.g., Happy Seeder, PUSA Decomposer), ex-situ biomass utilization, and circular economy models, evaluating their environmental efficacy, scalability, cost-effectiveness, and alignment with India's net-zero by 2070 commitment. The paper identifies persistent adoption barriers, from limited access to machinery and subsidies to behavioural inertia and gendered labor constraints. It also underscores residue management's strategic role in climate-smart agriculture, carbon sequestration, and rural livelihoods. The review concludes with actionable policy recommendations aimed at institutional convergence, digital innovation, carbon finance integration, and inclusive farmer outreach, reframing residue not as waste, but as a resource critical to sustainable agricultural transformation.**

Keywords— **Biomass utilization; Crop residue management; Climate-smart agriculture**

I. INTRODUCTION

India's agricultural sector, which supports over 50% of the national workforce and contributes significantly to the Gross Value Added (GVA), annually produces more than 500 million tonnes of crop residues. While a portion of this biomass is traditionally used for fodder, composting, or energy, an estimated 127 million tonnes remain surplus, largely due to changing agronomic practices, increased mechanization, and weakening agro-livestock linkages [1]. A substantial share of this surplus, particularly from paddy and wheat, is disposed of through open-field burning, a practice that is most pervasive in the Indo-Gangetic Plains (IGP), particularly in Punjab, Haryana, and Uttar Pradesh [2]. In the 2022–23 cycle alone, Punjab generated 19.99 million tonnes of paddy straw, with 7.49 million tonnes burned across 12.57 lakh hectares, while Haryana reported 0.75 million tonnes burnt, despite demonstrable improvements in in-situ management [3]. This method of disposal, though expedient, presents a multitude of environmental, agronomic, and public health risks. Studies have linked stubble burning to the deterioration of air quality [4], [5], estimating that up to 44% of Delhi's $PM_{2.5}$ concentrations during the post-monsoon period originate from residue burning. The practice also contributes significantly to greenhouse gas (GHG) emissions, releasing between 15 and 20 million tonnes of CO_2-equivalent annually, including short-lived climate pollutants such as methane (CH_4) and nitrous oxide (N_2O), with global warming potentials 28 and 265 times greater than CO_2, respectively [6]. Furthermore, empirical evidence indicates that burning one tonne of paddy straw leads to the loss of approximately 5.5 kg of nitrogen, 2.3 kg of phosphorus, 25 kg of potassium, and 1.2 kg of sulfur, in addition to damaging soil organic carbon and microbial biodiversity [7]. These environmental costs are compounded by severe health outcomes, including increased incidence of respiratory and cardiovascular diseases, and a number of premature deaths annually in India attributed to air pollution from agricultural burning [8], [9].

A considerable body of research has emerged to address these issues, evaluating a spectrum of sustainable crop residue management (CRM) practices. In-situ mechanized options such as the Happy Seeder and Super Straw Management System have shown promising results in enhancing soil structure and reducing GHG emissions [10], [11], [12], [13] while microbial interventions like the PUSA Decomposer accelerate biodegradation of residues in the field [14], [15]. Ex-situ approaches, ranging from briquetting and pelletization to biomass-based energy generation, have been promoted through national schemes like SATAT and the National Bio-Energy Mission [16], [17]. Nevertheless, these solutions remain under-adopted due to financial barriers, limited rural infrastructure, low farmer awareness, and weak inter-agency policy coordination. Most scholarly and policy discourse continues to focus on the rice-wheat systems of the IGP, with minimal attention paid to residue management in coarse cereals, pulses, oilseeds, and sugarcane grown in southern and central India. Similarly, very few studies examine the integration of CRM with carbon financing frameworks, the circular bioeconomy, or India's long-term emissions reduction commitments [4], [12], [18], [19], [20].

In light of these gaps, this paper provides a comprehensive review that goes beyond technological assessments to situate residue management within broader frameworks of climate change mitigation, rural livelihoods, and environmental governance. The novelty of this study lies in its integration of the latest operational guidelines, comparative evaluation of CRM practices across multiple metrics, including environmental impact, cost-effectiveness, and farmer accessibility, and its forward-looking emphasis on policy reform, institutional convergence, and region-specific solutions. It also introduces underexplored avenues such as public-private partnerships in biomass aggregation, digital platforms for custom hiring, and carbon credit generation through soil carbon enhancement and residue-based sequestration. The objectives of this paper are fivefold: first, to critically evaluate the agronomic, economic, and environmental performance of prevailing and emerging CRM alternatives; second, to identify systemic adoption barriers rooted in policy, infrastructure, finance, and behaviour; third, to examine the alignment of CRM strategies with India's nationally determined contributions (NDCs) and net-zero ambitions; fourth, to recommend actionable policy and institutional frameworks that promote scalable and inclusive adoption; and finally, to highlight critical research gaps, especially in relation to under-studied cropping systems, long-term soil health impacts, and climate-finance linkages. By reframing crop residue not as waste but as a valuable bioresource, the paper aims to underscore its pivotal role in transforming Indian agriculture into a more sustainable, climate-resilient, and economically inclusive system.

II. METHODOLOGY

This review employs a narrative and comparative critical review methodology (Figure 1), drawing on peer-reviewed journal articles, government policy documents, institutional reports, and case studies. A comprehensive literature search was conducted across Scopus, Web of Science, Google Scholar, and ScienceDirect using search terms including "crop residue management," "stubble burning," "Happy Seeder," "bio-decomposer," "biomass utilization," and "climate-smart agriculture in India." The search was restricted to English-language publications from 2005 to 2024, with a final inclusion of 112 relevant sources. The analytical framework focuses on five thematic areas: (i) comparative assessment of alternative practices; (ii) barriers to adoption; (iii) national and state-level policy frameworks; (iv) climate change integration; and (v) innovation and future directions. The review follows the PRISMA guidelines for transparency and quality.

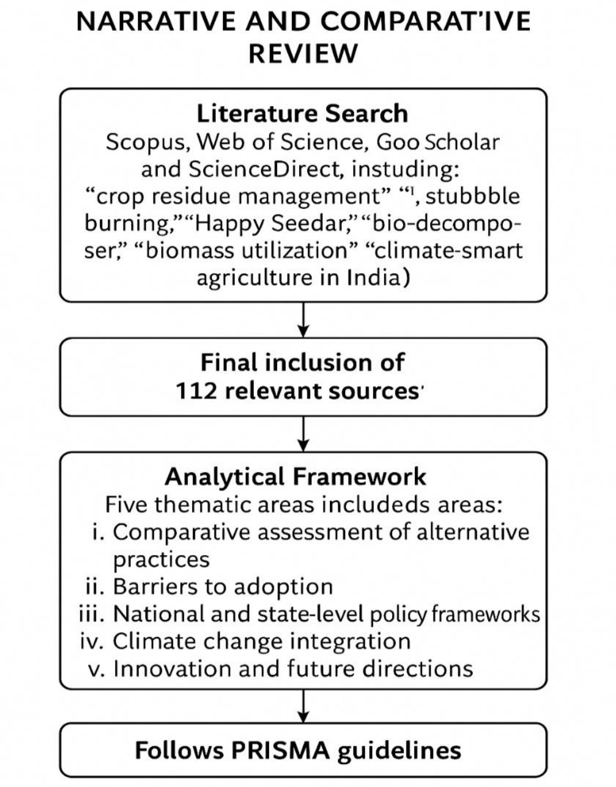

Figure 1: Methodology adopted for literature synthesis

2. Crop Residue Burning In India: Scope and Implications

2.1 Sources and Extent

India produces a vast quantity of agricultural biomass, with Punjab, Haryana, Uttar Pradesh, Madhya Pradesh, Maharashtra, and Tamil Nadu among the highest contributors to crop residue generation as shown in figure 2 [21]. According to study [22], an estimated 127 million tonnes of surplus crop residue are generated annually, of which approximately 23% is openly burnt in fields.

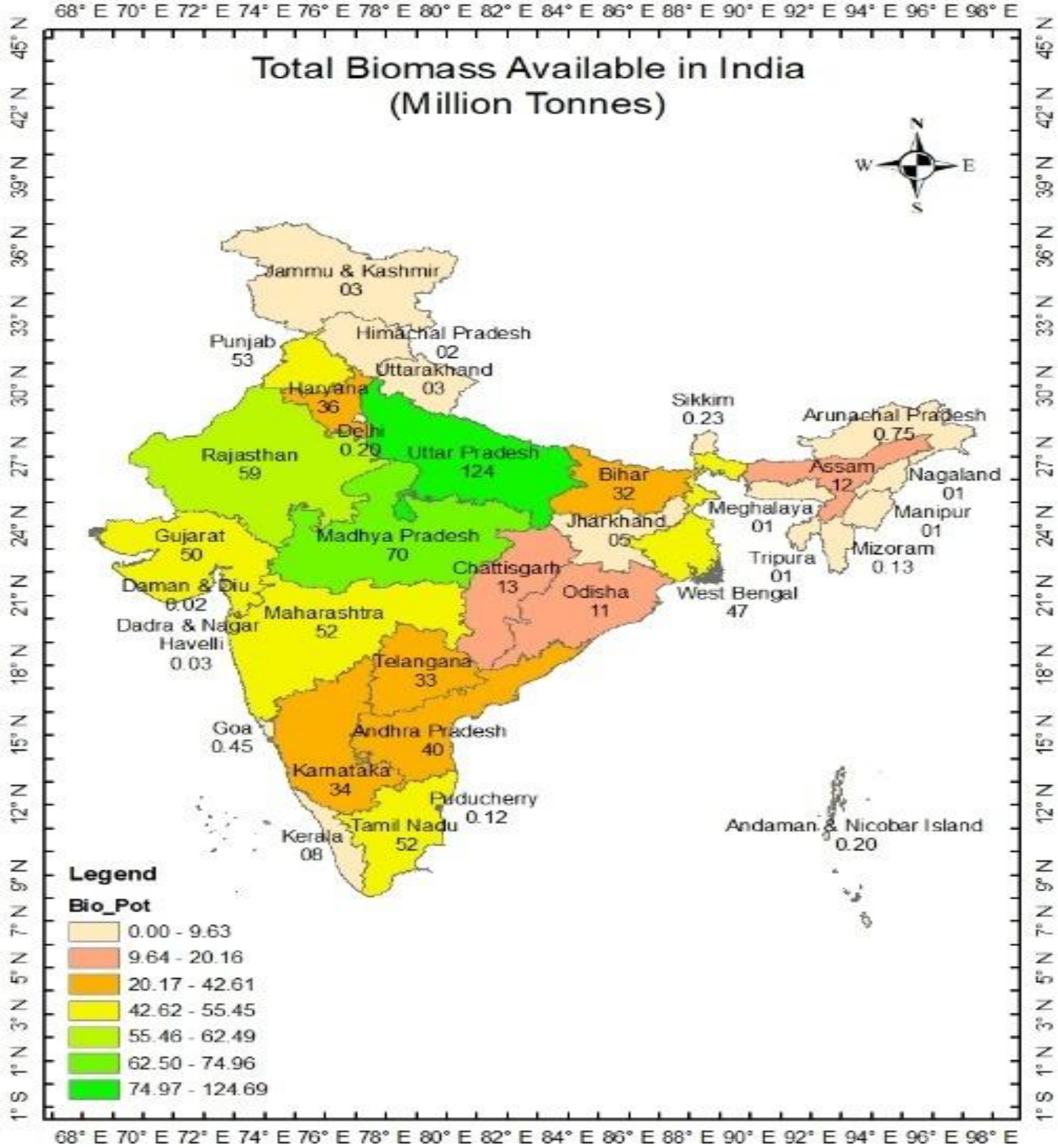

Figure 2. State-wise distribution of total biomass availability in India (in million tonnes)

Residue burning is especially rampant in paddy-wheat systems, where narrow timeframes between the kharif and rabi seasons incentivize rapid field clearance as shown in table 1 [23]. In Punjab alone, over 19 million tonnes of paddy straw are generated each year, and more than 70% of it is traditionally burnt [24]. According to the latest operational guidelines, Punjab generated approximately 19.99 million tonnes (Mt) of straw in 2022–23, of which 7.49 Mt were burned, accounting for over 12.57 lakh hectares of affected area. Haryana produced 7.00 Mt of straw, with 0.75 Mt burnt over 2.15 lakh hectares. In the NCR region of Uttar Pradesh, over 27.70 Mt of straw were generated as shown in figure 3, though precise burned quantities were not provided [25]. This reinforces the spatial concentration of residue burning in the Indo-Gangetic Plain (IGP), particularly in the rice-wheat intensive belts of Punjab and Haryana.

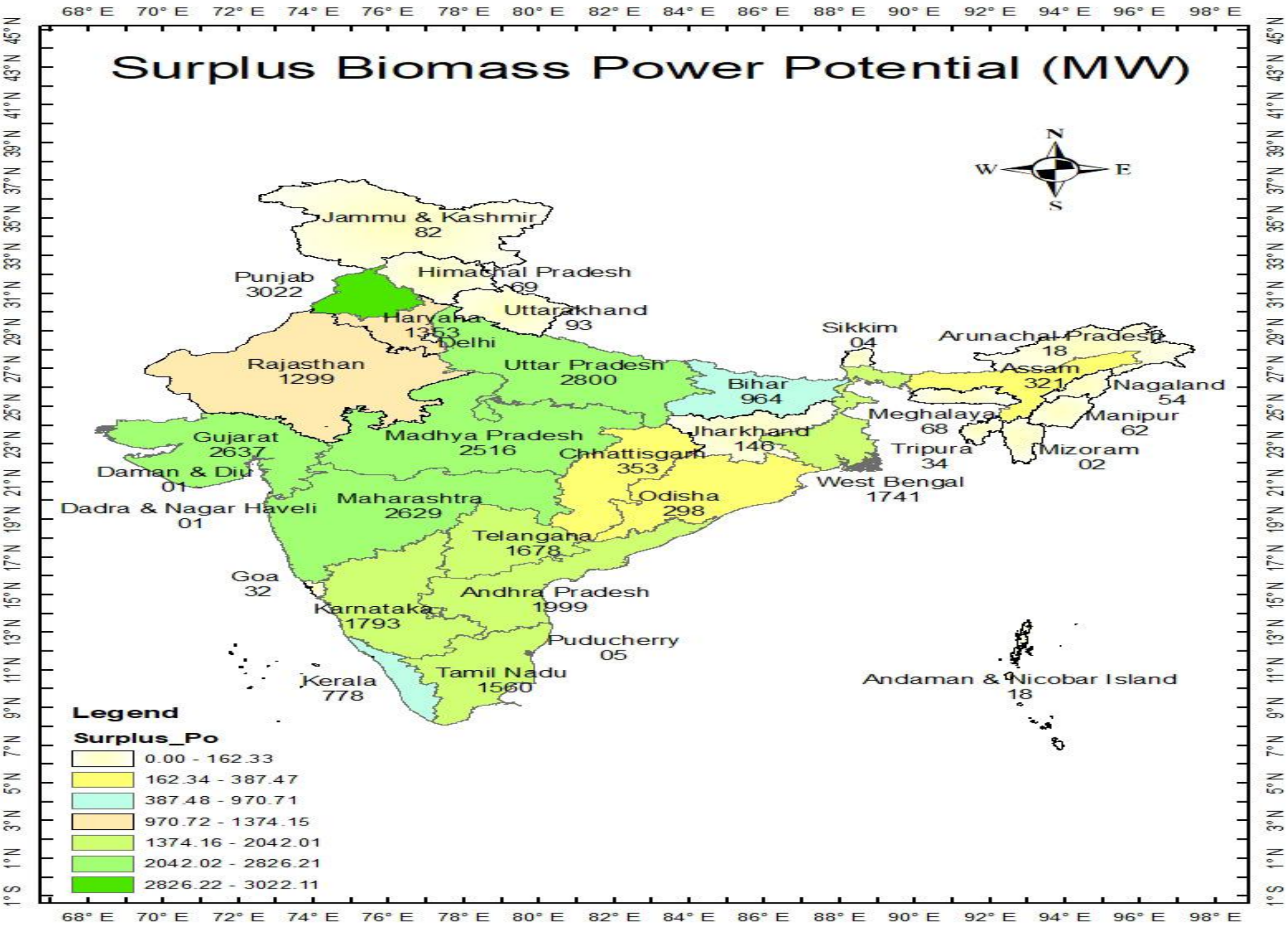

Figure 3. Surplus biomass power potential across Indian states (in megawatts).

Table 1: Scale of Stubble Burning in Indo-Gangetic Plains [3]

State	Straw Generated (MT)	Straw Burnt (MT)	Burnt Area (lakh ha)
Punjab	19.99	7.49	12.57
Haryana	7.00	0.75	2.15
Uttar Pradesh (NCR)	27.70	—	>0.67

2.2 Motivations behind Burning

The predominant drivers of residue burning are economic and logistical. The cost and labor involved in manual or mechanized residue collection are often prohibitive, especially for small and marginal farmers who constitute over 86% of India's farming population [12]. The rapid mechanization of harvesting, particularly through combine harvesters, has led to shorter crop cycles and a larger volume of loose straw that cannot be reused easily for fodder [17], [26]. Additionally, the lack of localized infrastructure for ex-situ utilization, such as biomass plants or straw collection centres, limits alternatives for residue disposal [12]

2.3 Environmental and Health Impacts

Some environmental and health impacts of crop residue burning are depicted in figure. 3. Burning of crop residues is a major source of air pollution, including particulate matter and carbonaceous species (e.g., $PM_{2.5}$, PM_{10}), carbon monoxide (CO), methane (CH_4), precursors of ozone, and polycyclic aromatic hydrocarbons (PAHs) [4], [11], [13], [27]. According to study [28], the contribution of stubble burning was estimated to be up to 44% of $PM_{2.5}$ in Delhi during a few days in October–November. For the climate variables, 70% of the carbon was released as CO_2, 7% as carbon monoxide, 0.66% as methane, and 2.09% of N as nitrous oxide (N_2O), this last is much more potent than CO_2, with a global warming potential 265 times higher compared to CO_2 [29]. These emissions have measurable impacts on India's climate ambitions, especially with respect to its NDCs. The effects of burning of crop residues on the environment are serious in nature and heterogeneous. It has recently been estimated that from burning one tonne of paddy straw, around 3 kg of particulate matter, 60 kg of CO, 1,460 kg of CO_2, 199 kg of ash and 2 kg of SO_2 are released. Such emissions are one of the major sources of environmental and air pollution (as shown in table 2) and cause a rise in the cases of prevalence of respiratory and cardiovascular diseases and also eye and skin diseases. In terms of public health, the study finds that agricultural burning-attributable air pollution prematurely kills 3 million people globally, with 44,000-98,000 agricultural burning-induced airborne particles exposure-related deaths occurring in India each year. The environmental damage from residue burning is not just limited to air pollution. Field experiment-based estimations suggest that burning one tonne of rice straw results in loss of 5.5 kg of nitrogen, 2.3 kg of phosphorus, 25kg of potassium, and 1.2 kg of sulphur which are essential nutrients of soil fertility and crop productivity. These losses are exacerbated by the removal of soil microbial communities by the high surface temperatures during burning, which results in long-term soil organic carbon degradation.

Moreover, burning affects soil health by destroying essential nutrients and beneficial microorganisms. Continuous burning reduces soil organic carbon, deteriorates soil structure, and increases nutrient runoff, necessitating higher fertilizer application as shown in figure 4. The thermal shock also disrupts the micro-ecosystem, leading to long-term yield declines.

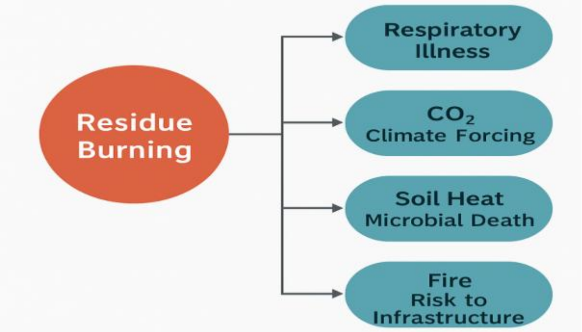

Figure 4: Environmental and Health Effects of Crop Residue Burning: A Systematic View

2.4 Contribution to Climate Change

Open-field residue burning is a source of short-lived climate pollutants and long-term greenhouse gases. It releases CO_2, but more critically, CH_4 and N_2O, which have global warming potentials 28 and 265 times greater than CO_2, respectively [6]. A study [30] states that residue burning contributes nearly 176 million tonnes of CO_2 equivalent emissions annually. This practice directly undermines India's commitment to its Nationally Determined Contributions (NDCs), particularly in reducing GHG intensity and enhancing carbon sinks through sustainable agriculture. Moreover, black carbon emissions from burning contribute to regional climate feedback loops by affecting monsoonal patterns and glacial melting in the Himalayas.

Table 2. State-wise CO_2eq emissions from crop residue burning, comparison between 2011 and 2020. Adapted from [6]

State/union territory	CO_2eq ($Gg.yr^{-1}$)		State/union territory	CO_2eq ($Gg.yr^{-1}$)	
	2011	2020		2011	2020
Andaman and Nicobar Islands	0	0	Karnataka	182.12	116.62
Andhra Pradesh	776.26	689.62	Kerala	0	0.71
Bihar	424.2	406.48	Lakshadweep	0	0
Chandigarh	0	0	Madhya Pradesh	2829.55	9611.2
Chhattisgarh	22.51	2.18	Maharashtra	300.99	13.39
Dadra and Nagar Haveli	0	0	Odisha	41.25	2.57
Daman and Diu	0	0	Puducherry	0	0
Delhi	0	0.76	Punjab	10,367.82	15,119.03
Goa	0	0	Rajasthan	497.56	3102.99
Gujarat	313.15	292.1	Tamil Nadu	11.52	65.34
Haryana	2344.59	2602.82	Telangana	0	220.66
Himachal Pradesh	0.245	0.11	Uttar Pradesh	1056.18	1342.76
Jammu and Kashmir	0.98	0.22	Uttarakhand	67.86	190.528
Jharkhand	2.86	2.7	West Bengal	100.88	53.03
			All India	19,340.30	33,833.91

2.5 Comparative Analysis of Crop Residue Management Practices in the Indo-Gangetic Plain (IGP): Environmental and Economic Perspectives (2020–2025)

Among all cultivated regions in South Asia, the Indo-Gangetic Plain (IGP) holds the distinction of being both the most productive and extensively farmed area because it depends on the rice-wheat farming system. The widespread environmental problems due to the open burning of crops have made crop residue management (CRM) an essential topic for sustainable agricultural practices throughout the region. The study merges results from peer-reviewed scholarly works (2020-2025) to understand the environmental and economic consequences of different CRM methods, as shown in Table 3. Studies on crop residue management reveal a strong emphasis on research about the rice-wheat cropping pattern because this cultivation system leads both spatially and politically in Punjab, Haryana, Uttar Pradesh, and Bihar [23], [31], [32]. Research on crop residue management mainly focuses on wheat and rice cultivation while neglecting crucial investigation regarding crop residue dynamics and management strategies for other agricultural crops. Farmer communities continue to choose conventional burning as their main operation method because it offers economic benefits during the initial stages despite its overall environmental drawbacks. The long-term use of this method results in environmental degradation. According to Kaur et al. [20], the harvesting method by stubble burning causes significant environmental problems by polluting the environment with pollutants, deteriorating the quality of soil, and loss of nutrients. No-till with residue retention, including practices with the Happy Seeder, have demonstrated positive results in terms of reduced emissions and enhanced soil structure. Several reports from Das et al. [19] and Walia et al. [33] report that these farming practices are more efficient in conserving energy and maintain sustainable crop production systems in the long term.

A combination of conservation agriculture (CA) practices including minimal tillage with residue retention and crop diversification has emerged as a recognized concept for enhancing both water retention and biodiversity by building up soil organic carbon. Research by Jat et al. [34] and Kumar et al. [23] recommended CA as an effective and sustainable practice for rice -wheat systems. The CRP assessment, so far, has not accounted for benefits of pulses or oilseeds or alternative crop rotations and given scant attention to existing CRP analyses. The application of residue to soils increases organic matter but normally requires additional fuel, cost, and labor. Challenges include the fact that flooded rice paddies become anaerobic and produce methane emissions [35]. Developing crop residue utilization has proven effective for soil microbial processes, water conservation and weed control, although most work has been conducted on the major cereals [18]. Data-based and efficient farming practices reflect the advances of precision nutrient and residue integration [20] and resource conservation technologies [36]. Research is needed to fully explore how these methods can enhance nitrogen use efficiency and decrease environmental impacts for non-rice and non-wheat crop systems. The practice of integrating legume crops with conservation systems. Kumar et al. [37] presents a method to decrease synthetic fertilizer consumption while improving soil health. Evidence shows that CRM needs additional research on various agriculture systems beyond rice-wheat systems, despite current findings. The research landscape of sustainable CRM in the IGP became notably abundant from 2020 to 2025, yet the study distribution remained substantially unfavorable toward rice and wheat crops. Research about residue management initiatives for maize, sugarcane, pulses, and oilseeds represents a significant gap within the literature since scholars have primarily examined rice and wheat residue practices. Further studies need to take a broader perspective, which includes all farming systems in the Indo-Gangetic area, to understand the complete impact of CRM on agroecology.

Table 3: Comparative Analysis of Crop Residue Management Practices in the Indo-Gangetic Plain (IGP)

CRM Practice	Crop	Environmental Impact	Economic Outcome	Recent Studies (2020–2025)
Burning	Rice-Wheat	High GHGs, loss of soil nutrients, severe pollution	Short-term cost saving; long-term yield decline	[20]
Zero Tillage + Residue	Rice-Wheat	Reduced CO_2 & CH_4; improved SOC and biodiversity	Higher profitability, less diesel use	[19]
In-situ Management (Happy Seeder)	Rice-Wheat	Avoids burning, improves air quality, and soil health	Operational savings, higher income	[33]
Conservation Agriculture	Rice-Wheat-Maize	Improves soil fertility, carbon storage, and biodiversity	High ROI, stable yield, better resilience	[34]
Residue Incorporation	Rice-Wheat	Moderate CH_4, improves	Fuel-intensive, long-term	[38]

		soil C/N, higher water retention	fertility benefit	
Mulching with Straw	Rice-Wheat	Retains moisture, improves microbial diversity	Slightly increased yield; cost of mulching machines	[18]
Precision CRM + Nutrients	Rice-Wheat	Reduces N leaching; boosts NUE	Cost-effective input use, higher yields	[20]
Resource Conservation Tech. (RCTs)	Rice-Wheat	Overall system GHG reduction, energy-efficient	Better returns than conventional systems	[36]
Pulses Integration + CA	Rice-Wheat-Pulse	Enhances soil N, reduces water footprint	Cost-saving in fertilizer; better net returns	[37]
Residue Removal (Controlled)	Rice-Wheat	Reduces burning but risks nutrient mining	Profits from biomass sales require nutrient compensation	[33], [39]

III. OVERVIEW OF SUSTAINABLE ALTERNATIVES TO RESIDUE BURNING

India's chronic reliance on open-field crop residue burning has triggered significant environmental, health, and agricultural sustainability concerns. In response, various sustainable residue management strategies have been developed and piloted across different agro-ecological zones. These alternatives can be broadly categorized into four domains: in-situ management, ex-situ utilization, biological decomposition, and circular economy innovations. The effectiveness of each method is contingent upon regional agronomic practices, socio-economic contexts, mechanization levels, and policy support.

3.1 In-Situ Management Practices

In-situ residue management involves incorporating or retaining crop residues within the field, either by soil integration or surface application, thus avoiding transportation and enabling nutrient recycling.

3.1.1 Happy Seeder (HS) Technology

The Happy Seeder (HS) is a tractor-operated implement designed to sow wheat directly into the paddy residue without needing prior burning or residue removal [40]. Developed through the collaborative efforts of Commonwealth Scientific and Industrial Research Organization (CSIRO) engineers in Griffith, Australia, and the Punjab Agricultural University and International Maize and Wheat Improvement Center (CIMMYT), the machine cuts and lifts the straw, sows seeds, and deposits straw as mulch [41]. Agronomic Benefits of HS are that the mulched layer acts as a natural insulator, reducing evapotranspiration, suppressing weed growth, and enhancing soil organic matter. Empirical studies show improved yields (4–7%), reduced input costs, and enhanced microbial diversity [40], [42]. Whereas, constraints of the HS are that it requires tractors with ≥45 HP, limiting accessibility for smallholders. High capital cost (INR 1.5–2 lakhs) often deters adoption without subsidies or custom hiring centers (CHCs) [40], [43], [44], [45].

Super Straw Management System (Super SMS)

This equipment is attached to combine harvesters and chops the straw post-harvest, spreading it evenly across the field. The uniformity facilitates later sowing with tools like the Happy Seeder or Zero Till Seed Drill [43]. The mechanism involves breaking down the straw length to ~5–7 cm and distributing it. Super SMS ensures unobstructed seed placement. The government institution adopted strategies such as the Crop Residue Management (CRM) Scheme, a Central scheme that has subsidized Super SMS, increasing usage, particularly in Punjab and Haryana [3]

3.1.3 Zero Tillage with Residue Retention

Zero tillage involves direct sowing without plowing, often coupled with surface residue retention [46]. This conservation agriculture practice improves soil structure, reduces soil compaction, and lowers diesel usage by up to 80% per hectare [47]. The limitations of this method are: weed management requires precision; farmers often rely on herbicides, leading to potential overuse and resistance.

3.1.4 Institutional Facilitation under NPMCR

The NPMCR proposes a comprehensive strategy to facilitate in-situ residue management through technology dissemination, financial support, and institutional mechanisms. Central to this approach is the promotion of resource-conserving implements such as the Happy Seeder, Zero-Till Seed-Cum-Fertilizer Drill, Turbo Seeder, and Straw Baling Machines, which are subsidized under schemes like the Rashtriya Krishi Vikas Yojana (RKVY). These technologies are further supported by the establishment of Custom Hiring Centres (CHCs) and Agricultural Service Centres (ASCs) to democratize access, particularly for small and marginal farmers who cannot afford capital investment in individual machinery [3]. In-situ incorporation of residues is thus positioned not only as a soil health strategy but also as an institutional entry point for mechanization and service innovation in rural India.

3.2 Ex-Situ Utilization Approaches

Ex-situ strategies aim to extract value from crop residues outside the field, transforming agricultural waste into energy, industrial input, or livestock feed.

3.2.1 Biomass-Based Power Generation

Paddy straw, sugarcane bagasse, and cotton stalks are used as feedstock for biomass power plants [17], [48]. Projects such as NTPC’s biomass co-firing initiative integrate agri-residue pellets with coal to reduce fossil fuel reliance [35]. Energy Potential: India’s surplus biomass can produce 18 GW of electricity, significantly contributing to renewable energy goals. Additional research indicates that the cumulative biomass power capacity in India may be over 35 GW by 2030, highlighting the role of biomass in India's renewable energy sector as shown in table 4 [17], [48]. The challenges faced are logistic hurdles in biomass aggregation, inconsistent moisture content, and low calorific value hinder full-scale operations.

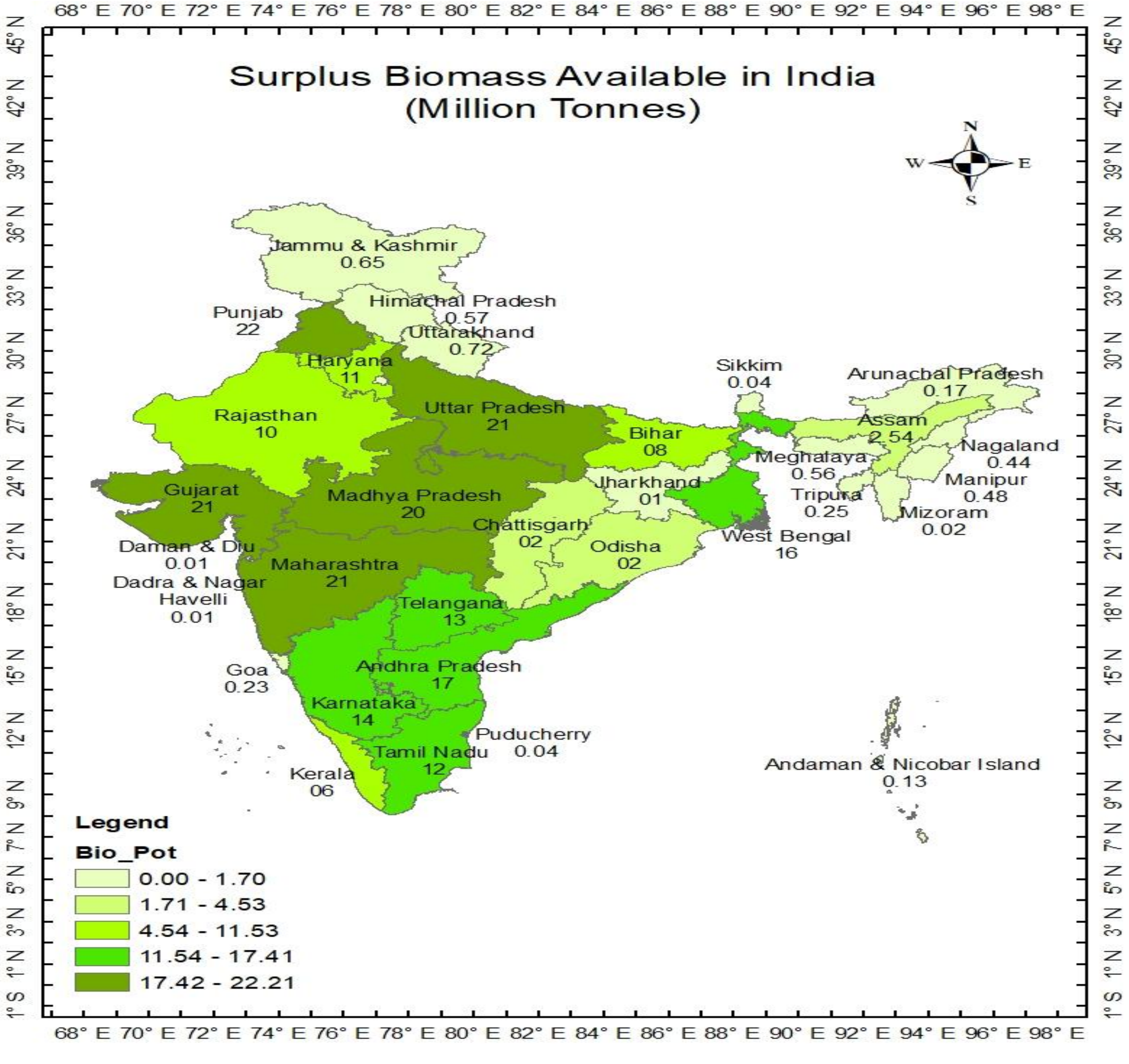

Figure 5. Surplus biomass availability across Indian states (in million tonnes).

A significant development under the ex-situ model is the proliferation of bioenergy projects using crop residues as feedstock as shown in figure 5. In Punjab, 13 biomass power plants (111.5 MW combined capacity) consume around 1.00 Mt of paddy straw annually, alongside 8 bio-CNG projects with a combined capacity of 0.3 Mt. The Bathinda bioethanol project and the Verbio biogas plant in Sangrur further add capacity of 100 KLPD and 33 TPD respectively. Haryana hosts a 100 KLPD 2G ethanol plant (Panipat) and 4 biomass power plants totaling 49.8 MW. Nationally, NTPC’s plants at Dadri and Jhajjar collectively demand over 1.2 Mt/year of biomass pellets, contributing to a broader national requirement exceeding 5,000 tonnes/day [3].

3.2.2 Briquetting and Pelletization

Briquetting machines compress crop residues into dense, transportable biofuels suitable for boilers, thermal plants, and brick kilns [49]. These biofuels have industrial demands, such as the cement and steel industries are increasingly adopting agri-biofuels to meet environment, social, and governance (ESG) targets [50]. However, the economic viability requires aggregation centers, pre-processing infrastructure, and assured market linkage, often lacking in rural India [48].

3.2.3 Use in the Pulp, Paper, and Packaging Sector

Cellulose-rich residues such as wheat straw and bagasse are excellent raw materials for paperboard and sustainable packaging [51], [52], [53]. Startups like Ecoware and PadCare Labs are using stubble to produce biodegradable products, reducing reliance on wood pulp. Ecoware makes use of plant-based materials to produce compostable and biodegradable straws and cutlery, providing eco-friendly substitutes for traditional plastic products. In the same manner, PadCare Labs has also created a recycling method that converts used sanitary products into useful resources, promoting sustainability and circularity in the menstrual hygiene industry.

3.2.4 Fodder Processing and Livestock Bedding

While coarse residues (e.g., maize, bajra stalks) are traditionally used as cattle feed, paddy straw is often rejected due to silica content, low protein level, and poor digestibility, making it unpalatable for cattle. New interventions involve urea treatment and microbial enrichment to enhance its digestibility and reduce enteric methane emissions [54]. Farmers are now often using treated paddy straw and other residues as livestock bedding, since they are cleaner and environmentally friendly compared to plastic materials.

3.2.5 Waste-to-Energy Conversion of Crop Residues

The waste-to-energy concept presents a beneficial model for processing surplus agricultural waste to create available energy while helping India increase its renewable energy supply and protect its environment. The conversion of biomass materials, including rice straw, wheat husks, sugarcane trash, and cotton stalks, through WtE techniques produces multiple energy output forms such as electrical power, bio-CNG, ethanol, and syngas, which turn former waste into industrial raw materials [55]. India annually generates 141 million tonnes of crop residues, but a considerable amount goes unused or is burned because of poor management techniques. The biomass from these residues could generate 18–23 GW of energy if used to produce biomass-based electricity [56]. NTPC conducts biomass co-firing through its program that mixes agri-residue pellets with coal at thermal power plants to minimize carbon emissions from standard energy generation [57]. A program called Sustainable Alternative Towards Affordable Transportation (SATAT) promotes the decentralized development of compressed bio-gas (CBG) plants by the Ministry of Petroleum and Natural Gas (MoPNG) for utilizing agri-residues as plant feed [55].

The WTE sector, however, is not without its challenges. Key operational barriers include:

- High logistical costs associated with biomass collection, preprocessing, and transportation due to its bulk and low energy density.
- Moisture variability in crop residues, particularly paddy straw, affects calorific value and combustion efficiency.
- Limited rural infrastructure, including lack of aggregation centers, drying yards, and storage silos.

Furthermore, extraction of residues from fields for energy as conversion also prompts the problem of sustained soil nutrient depletion by the removal of OM that would have maintained soil fertility and soil carbon (C) sequestration on a long-term basis [54], [58]. This means that sustainable application of WtE systems requires a “nutrient budgeting framework” as well as INM strategies to compensate for the nutrient losses through harvest of the biomass [59]. National Policy for Management of Crop Residue (NPMCR) promotes WtE technologies. Financial stimulation mechanisms, VGF, and APEX (Accelerated Power Project) also important to mobilize private sector investment in biomass energy projects [25]

Despite these challenges, WtE technologies present an important avenue for promoting circular bioeconomy principles and reducing the burning of open-field residues. They can play a transformative role in India's transition toward climate-resilient and resource-efficient agriculture when integrated with digital biomass marketplaces, decentralized storage, and farmer cooperatives.

Table 4. State-wise Paddy Straw Generation and Management in Punjab, Haryana, and Uttar Pradesh (2022–23) Source: [3]

State	Total Cultivable Area in Kharif (lakh ha)	Area under Kharif Paddy (lakh ha)	Paddy Straw Generated (Million Tonnes)	Paddy Straw Managed (Million Tonnes)	Paddy Straw Burnt (Million Tonnes)	Paddy Area Burnt (lakh ha)
		Total	Basmati	Non-Basmati		In-situ
Punjab	42	31.43	4.36	27.07	19.99	9
Haryana	38	13.9	7.32	6.58	7	5.15
Uttar Pradesh	128.73	59.99	25.89	34.1	27.7	—

3.3 Biological and Composting-Based Solutions

These approaches promote decomposition of residues on-site, harnessing microbial agents to recycle nutrients and improve soil organic carbon.

3.3.1 Microbial Decomposers (e.g., PUSA Decomposer)

Developed by IARI, the PUSA Decomposer consists of fungal consortium tablets (Trichoderma spp., Aspergillus spp., etc.) that accelerate residue breakdown. The time taken by the PUSA decomposer to decompose the residue is 20-25 days under optimum conditions. Field Results showed that trials in Delhi-NCR in 2020 and 2021 reduced stubble volume by 70–80% and improved NPK availability in soil [14], [15]. The Constraints of this decomposer are that they are moisture and temperature-sensitive; sowing delays in colder regions reduce adoption.

3.3.2 Composting and Vermicomposting

Composting and vermicomposting are labor-intensive, low-cost alternatives, ideal for small farms or peri-urban zones. Vermicomposting enriches nutrient content and enhances microbial biomass carbon, thereby improving the health of the soil. However, it’s unsuitable for large-scale paddy straw due to its high C:N ratio and silica content, making it difficult to decompose [60]. To overcome these limitations, innovation in Co-composting techniques, such as paddy straw mixed with animal dung or municipal organic waste, can balance nutrient content and reduce emissions during decomposition [61].

3.4 Circular Economy and Residue Valorization

A systemic transformation toward a bioeconomy involves reimagining crop residues not as waste but as raw material for a wide range of industries.

3.4.1 Agro-Industrial Symbiosis

- Examples: Use of straw in biochar production, mushroom cultivation, bioplastics, and even textile fibres. Rice straw can now be turned into biochar and used for environmental purposes [42]. Evidence has been found that utilizing mushroom waste and fibers in textiles and creating biochars with torrefaction is possible [62].
- Economic Models: Private platforms like Biofuel Circle connect farmers with processors via digital biomass marketplaces, making it easier and more secure to supply biomass and biofuels.

3.4.2 Carbon Financing and ESG Alignment

Voluntary carbon markets are exploring residue management as a mitigation measure, offering farmers additional income through carbon credits. Initiatives in India have pointed out that carbon farming can help farmers receive extra financial incentives from using sustainable practices [63]. Companies are integrating residue valorization into Corporate Social Responsibility (CSR) and Environmental. Social and Governance (ESG) reporting gains both environmental and reputational value. The results of several studies reflect that ESG disclosures help boost corporate performance in India. [64].

A diverse set of residue management strategies exists, ranging from field-level mechanical solutions to industrial-scale resource valorization. While each method offers distinct agronomic, environmental, and economic advantages, their deployment is currently fragmented and hindered by systemic barriers. A comparative evaluation, as discussed in the next section, will help delineate these alternatives' context-specific efficacy, feasibility, and climate relevance.

IV. COMPARATIVE EVALUATION OF PRACTICES

The availability of diverse crop residue management practices in India necessitates a critical comparison to assess their effectiveness, scalability, and alignment with national sustainability goals as shown in table 5. This section presents a comparative evaluation of key in-situ, ex-situ, and biological alternatives to open burning, based on the following criteria: environmental impact, cost to farmers, ease of adoption, impact on soil health, suitability for smallholders, and climate mitigation potential.

Table 5. Comparative Evaluation of Crop Residue Management Practices in India

Criteria	Happy Seeder	PUSA Decomposer	Composting/ Vermicomposting	Biomass Power/WtE Plants	Pelletization/Briquetting	Biochar Production	Open Burning (Status Quo)
Type	In-situ (mechanical)	In-situ (biological)	Ex-situ (organic recycling)	Ex-situ (thermal energy recovery)	Ex-situ (solid fuel conversion)	Ex-situ (pyrolysis-based carbonization)	In-situ (combustion)
Primary Feedstock	Paddy straw, wheat straw	Any crop residue (esp. paddy)	Straw, organic matter	Paddy, sugarcane, cotton stalks	Cereal straws, cotton, pulses	Any dry lignocellulosic residue	All field residues
CapEx (Initial Cost)	High (~₹1.5–2.5 lakh per unit)	Low (~₹200–₹300/ha per application)	Very Low	Very High (₹2–5 crore for 1 MW unit)	Moderate (~₹30–50 lakh per unit)	High (₹1–2 crore per pyrolysis unit)	Nil
OpEx (Running Cost)	Moderate (diesel, maintenance)	Very Low	Low (labor-intensive)	High (collection, drying, operations)	Moderate (aggregation + preprocessing)	Moderate-High	Low (labor/fire)
Subsidy/Policy Support	High (CRM Scheme, CHCs)	Moderate (State pilots, MoAFW support)	Low (MGNREGA for compost pits)	Moderate (SATAT, NTPC biomass policy)	Moderate (state MSME & bioenergy programs)	Low–Emerging (voluntary carbon markets)	Banned (NGT, State Govts)
Ease of Adoption	Moderate (requires ≥45HP tractors, skilled use)	High (sprayable, farmer-friendly)	Moderate (labor-intensive, seasonal)	Low (institution-driven, needs aggregation)	Moderate (requires preprocessing infra)	Low (technology-intensive)	Very High (traditional practice)
Time to Implement	Fast (within same crop cycle)	20–25 days for decomposition	Slow (30–60 days depending on method)	Long (plant setup and logistics)	Medium (site establishment and sourcing)	Medium-High	Instantaneous
Impact on Soil Health	Very Positive (mulching, moisture retention)	Positive (improves SOC, NPK)	Positive (organic matter, microbial activity)	Neutral to Negative (removes residue)	Negative (removes biomass, potential leaching)	Positive (improves structure, carbon content)	Very Negative (microbial death, nutrient loss)
Environmental Impact	Very Low emissions (85% GHG reduction)	Very Low (no combustion involved)	Very Low (if done properly)	Moderate (emissions during transport & firing)	Moderate (combustion pollution risk)	Low (net carbon sequestration)	Very High (GHGs, PM, Black Carbon)
Climate Mitigation Potential	High (reduces CH_4, N_2O, enhances soil carbon)	High (eliminates need for burning)	Moderate (indirect, long-term)	Moderate-High (replaces fossil fuel)	Moderate (displaces coal/furnace oil)	High (eligible for carbon credits)	Negative (emits SLCPs, violates NDC goals)

Scalability	Moderate (dependent on machinery access)	High (low cost, field-based)	Low–Moderate (labor, land needed)	Moderate (needs feedstock access)	Moderate (logistics and processing hubs)	Low–Moderate (technology bottlenecks)	Ubiquitous but unsustainable
Suitability for Smallholders	Low (unless accessed via CHCs/FPOs)	Very High (cost-effective, simple)	Moderate (if supported by MGNREGA /SHGs)	Very Low (industrial scale only)	Low (needs aggregation & formal contracts)	Very Low (capital & tech intensive)	High (no alternatives perceived)
Circular Economy Contribution	Moderate (mulching closes nutrient loop)	High (on-farm carbon recycling)	High (waste-to-input conversion)	High (energy generation from waste)	High (industry use, fuels)	Very High (long-term carbon sink)	None
Revenue Potential for Farmers	Indirect (yield improvement, less input)	Indirect (better soil, cost savings)	Indirect (if sold as compost)	High (through biomass procurement contracts)	Moderate (feedstock sales)	Moderate (if linked to carbon markets)	None
Gender and Labor Inclusion	Low (male-dominated machinery use)	Moderate (women can apply)	High (labor intensive, women-involved)	Very Low (centralized, male-dominated)	Low (operational, male-run)	Very Low	High (informal, unpaid female labor)

Comparative evaluation of major crop residue management practices in India across agronomic, environmental, economic, technological, and institutional dimensions. The table is based on data compiled from multiple authoritative sources, including IARI, IPCC, MNRE.

4.1 Environmental Impact

In-situ management techniques, particularly the Happy Seeder and PUSA Decomposer, offer significant environmental benefits by preventing air pollution, preserving soil organic carbon, and minimizing greenhouse gas emissions. In contrast, biomass combustion, though cleaner than open burning, may still emit pollutants if not managed under controlled conditions.

- The Happy Seeder reduces particulate emissions and carbon dioxide equivalents by up to 85% when compared with traditional burning [40].
- Microbial decomposers, such as the PUSA Decomposer, eliminate the need for burning entirely and foster rapid decomposition with minimal environmental trade-offs [15], [65].
- Ex-situ options like biomass plants or pelletization reduce fossil fuel dependence but require energy input for transport, processing, and combustion, which can partially offset their environmental gains [66].

4.2 Cost to Farmers

Cost remains a significant determinant of adoption. The Happy Seeder and Super SMS require capital investment in machinery and are often accessible only to medium or large farmers unless supported by subsidies or Custom Hiring Centres (CHCs).

- PUSA Decomposer is highly cost-effective (approximately ₹200–₹300 per hectare) and requires no machinery, making it a viable option for smallholders [65].
- Ex-situ models often transfer the cost burden to intermediaries or require significant capital for collection, transportation, and processing infrastructure [67].
- Composting and zero tillage are relatively low-cost but demand more labor and time [46], [61].

4.3 Ease of Adoption

Biological decomposers score highly in terms of simplicity and low entry barriers. These can be applied without technical expertise, unlike mechanized options such as the Happy Seeder or Super SMS, which require tractors with specific [40] horsepower, skilled operators, and routine maintenance [7], [67], [68].

• Zero tillage also requires farmer training, especially in herbicide use and water management [46].

- Ex-situ solutions demand logistical arrangements for residue aggregation, which small-scale farmers cannot usually manage independently [69].

4.4 Soil Health and Agronomic Benefits

In-situ retention through mulching (as in Happy Seeder and zero tillage) improves soil structure, moisture retention, and nutrient cycling. This leads to enhanced productivity over time and reduced dependence on synthetic fertilizers [40], [44], [67].

- PUSA Decomposer enriches soil with decomposed organic matter and supports microbial diversity [7].
- In contrast, ex-situ residue extraction removes biomass that could otherwise replenish soil organic carbon, potentially leading to nutrient mining unless supplemented by compost or biofertilizers [61], [70].

4.5 Suitability for Small and Marginal Farmers

Marginal farmers, who make up over 85% of India’s agricultural population (Agricultural Census, 2015–16), are most affected by burning-related externalities and least capable of adopting mechanized solutions [7], [69].

- The PUSA Decomposer is particularly well-suited due to its affordability and simplicity [15], [65], [67].
- Composting is another low-tech, labor-intensive option available to resource-poor farmers [61].
- Mechanized in-situ tools are generally inaccessible without shared equipment or government support [45].

4.6 Climate Mitigation Potential

Residue management alternatives differ in their capacity to contribute to India's climate mitigation goals.

- Happy Seeder and decomposer-based approaches help in reducing direct GHG emissions from burning while enhancing soil carbon sequestration [7].
- Biomass power and pelletization offer indirect emission reductions by substituting fossil fuels [69].• Composting sequesters carbon in soils, albeit slowly, and may contribute to long-term climate resilience [61].

4.7 Comparative Evaluation Matrix

The assessments are derived from various studies including [11], [12], [13], [13], [15], [58], [67], [70], [71] which at a comparative scale evaluate different crop residue management options for cost, compatibility- to-soil health, and environmental compromise. This comparison is a reminder that a particular residue management strategy cannot be universally justified. Nevertheless, PUSA Decomposer and Happy Seeder exhibits the most encouraging trade-off in terms of agronomic, environmental and climate benefits [7], [68].

Table 6 Evaluation of Agricultural Practices and Technologies Based on Environmental Impact, Cost, and Other Key Criteria

Evaluation Criteria	**Happy Seeder**	**Super SMS**	**PUSA Decomposer**	**Biomass Power Plants**	**Pelletization & Briquetting**	**Composting**	**Zero Tillage with Mulch**
Environmental Impact	Very High	High	Very High	Moderate	Moderate	High	High
Cost to Farmer	High	Moderate to High	Very Low	High	High	Low	Low
Ease of Adoption	Moderate	Moderate	Very High	Low	Low	Moderate	Moderate
Soil Health Benefits	Very High	High	High	Low	Low	High	Very High
Suitability for Small Farmers	Low	Low	Very High	Very Low	Very Low	Moderate	Moderate
Climate Mitigation Potential	Very High	High	High	Moderate	Moderate	Moderate	High

However, the scale and inclusiveness of such tools depend on policy incentives, capacity building and financial accessibility [12]. The ex-situ systems are most suitable for the areas having higher residue density, infrastructure support, and industrial chains [12], [69]. A hybrid and location specific approach to both eco-logical and socio-economic factors is a prerequisite for a successful large-scale shift from burning residues to their sustainable utilization [43].

V. BARRIERS TO ADOPTION OF ALTERNATIVES

Despite the availability of effective and environmentally sound alternatives to residue burning, their adoption across

India remains limited and inconsistent. The barriers to implementation are complex and interrelated, spanning economic, institutional, technological, infrastructural, and socio-cultural domains [7], [12], [27], [68]. Addressing these barriers requires a multidimensional approach that aligns policy frameworks, market incentives, and local behavioural dynamics.

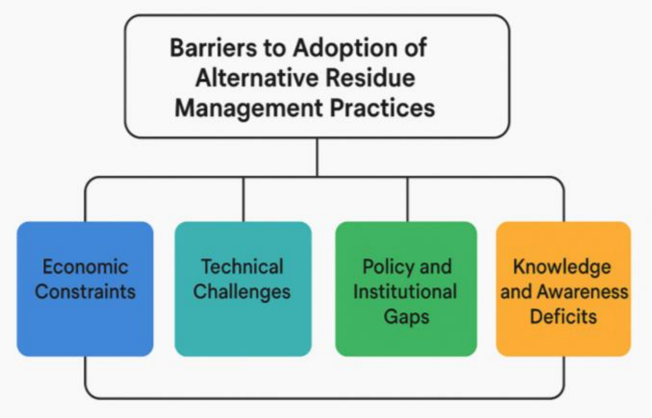

Figure 6: Barriers to Adoption of Sustainable Residue Practices in India

The dominant barriers that impinge on the livelihoods of the people can be classified into the following four main dimensions: economic constraints, technical constraints, policy and institutional gaps, and knowledge and awareness gaps as shown in figure 6. These linked constraints restrict the functional scalability and farmer acceptance of sustainable practices like composting, in-situ retention, and biomass valorization [7], [67].

5.1 Economic Barriers

5.1.1 High Initial Investment Costs

Many sustainable alternatives, especially mechanized in-situ technologies like the Happy Seeder, Super Straw Management System, and Zero Till Seeders, require significant capital investment. The cost of a Happy Seeder ranges from ₹1.5 to ₹2.5 lakh, often beyond the capacity of small and marginal farmers, who constitute over 85% of India's agricultural sector [40], [65]

5.1.2 Inadequate Access to Credit and Subsidies

Although government subsidy schemes under the Crop Residue Management (CRM) Scheme exist, they often face implementation delays, bureaucratic hurdles, and lack of awareness among beneficiaries. Smallholders, tenant farmers, and landless cultivators typically lack access to formal credit systems and remain excluded from institutional financing and subsidy frameworks [72].

5.1.3 Absence of Residue-Based Market Linkages

Ex-situ utilization approaches, such as biomass-to-energy or pelletization, depend on well-established value chains for procurement, transportation, and processing. In the absence of reliable markets and guaranteed procurement prices for crop residues, farmers are disincentivized to invest in residue collection or storage infrastructure [12], [26]. Despite progressive funding allocations under central and state schemes, the field-level uptake of sustainable technologies is impeded by fragmented fiscal flows and delayed disbursement cycles. The NPMCR explicitly calls for multi-ministerial resource mobilization, involving the Ministries of Agriculture, Environment, and Rural Development. While states like Punjab and Haryana have leveraged Annual Work Plans under RKVY to procure mechanized implements, such interventions remain isolated. The policy recommends convergence of schemes and decentralization of fund utilization to ensure timely access and localized adaptation of residue management solutions [3], [21].

5.2 Institutional and Policy Barriers

5.2.1 Fragmented Governance and Overlapping Mandates

Residue management falls under multiple ministries and agencies, including the Ministry of Agriculture, Ministry of Environment, Forest and Climate Change (MoEFCC), and State Departments of Agriculture and Pollution Control Boards. This fragmented governance structure leads to policy incoherence, redundancy, and ineffective enforcement of anti-burning regulations [66].

5.2.2 Inconsistent Implementation of Regulations

Although the National Green Tribunal (NGT) and Supreme Court have issued directives banning residue burning, enforcement remains weak at the local level due to lack of manpower, political will, and institutional capacity. Penal provisions under the Air (Prevention and Control of Pollution) Act are rarely enforced, especially in the face of electoral sensitivities and farmer protests [73]

5.2.3 Weak Integration with Climate and Rural Development Policies

Residue management is often treated in isolation rather than being embedded within broader climate action, agroecology, or rural livelihoods frameworks. The absence of synergy with Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) or carbon farming incentives further limits uptake among low-income farmers [12].

5.3 Technological and Infrastructure Barriers

5.3.1 Limited Availability and Maintenance of Equipment

The adoption of in-situ mechanized solutions is hindered by limited availability of high-horsepower tractors, delayed procurement cycles, and inadequate after-sales service or spare parts. Custom Hiring Centres (CHCs), though intended to bridge this gap, are unevenly distributed and often poorly maintained [40]

5.3.2 Poor Storage and Aggregation Facilities

Ex-situ residue utilization requires organized collection points, balers, transportation systems, and storage units to preserve the quality of biomass. In many rural regions, especially outside Punjab and Haryana, such infrastructure is either non-existent or underutilized due to high transaction costs [12], [70].

5.3.3 Lack of Adaptive Technologies for Diverse Agro-Climatic Zones

Most technologies have been developed for the rice–wheat system of the Indo-Gangetic Plains. There remains a dearth of scalable, affordable tools for coarse cereals, cotton, pulses, and sugarcane residues, which dominate in other states like Maharashtra, Karnataka, and Tamil Nadu [23], [26].

5.4 Socio-Cultural and Behavioural Barriers

5.4.1 Perception of Burning as Low-Cost and Convenient

Farmers consider residue burning to be a fast, free, and agronomically indifferent practice, especially before short-run costs are seen. Such perceptions are further encouraged by peer behaviour, untrained staff and customs that have been transmitted from generation to generation [74]. Behavioral economics could represent a new approach to addressing these problems in the design of policies. Using of Thaler and Sunstein’s ‘nudge’ framework, residue management policy could use light touch interventions, social comparisons, self-certification and default into non-burning programmes, that can change farmer behaviour without forcing them to do so. For example, requiring ‘non-burning certificates’ to be openly displayed in Gram Sabhas or using SMS-based community dashboards that show burning versus non-burning stats would use social proof to prompt adherence. Furthermore, presenting the benefits of CRM within aspirational narratives, like soil health for the future of the farmers’ children or cleaner air for the well-being of the village elders, may resonate with farmers' innate values [75].

5.4.2 Resistance to Change and Risk Aversion

Adopting new practices involves uncertainty, especially regarding yields, soil moisture dynamics, and pest cycles. Without demonstrable, location-specific success stories, farmers remain sceptical. Behavioural inertia is compounded by low literacy, limited extension services, and insufficient trust in institutional actors [12].

5.4.3 Gendered Dimensions and Labor Constraints

Residue management often intersects with gender roles in agriculture. Women, who are primary labor providers in smallholder farms, are often excluded from training programs, mechanization drives, and decision-making forums. Labor-intensive methods such as composting are also discouraged due to migratory trends and rising labor costs [7]. Sustainable residue management practices face barriers which stem from structural foundations along with behavioral aspects and surpass technological and financial elements. Any single supply-side mechanism such as machine subsidization will fail to achieve broad adoption without institutional transformation alongside development programs that provide financial assistance and training to develop sustainable attitudes. Multiple stakeholders, including farmers, private sector representatives, civil society organizations, and local authorities, need to work together to solve these system-wide constraints [40].

The ensuing part analyzes current Indian policies regarding these problems while outlining essential modifications to reduce execution obstacles. Sustainable practice adoption faces a substantial barrier from behavioural resistance. The NPMCR promotes two nudges to combat inert behavior by establishing farmer declaration methods that Gram Pradhans can verify for agricultural loan eligibility. The policy promotes both Self-Help Group (SHG) establishment and youth employment support for creating CHCs. It mandates mass media and field demonstrations during different seasons to spread knowledge that will merge with rural communities' value systems, thus transforming common agricultural practices across the region [3], [66].

VI. POLICY FRAMEWORK AND GOVERNMENT INITIATIVES

India has recognized the severity of crop residue burning and initiated various policy interventions, legal mandates, fiscal incentives, and technological schemes to address the problem. However, implementation inconsistencies, fragmented institutional roles, and lack of monitoring and integration have limited their effectiveness. This section reviews the current policy landscape, evaluates flagship programs, highlights state-led innovations, draws insights from international experiences, and identifies critical gaps.

6.1 National-Level Initiatives

6.1.1 National Policy for Management of Crop Residue (NPMCR)

Formulated by the Ministry of Agriculture and Farmers Welfare (MoAFW), the NPMCR emphasizes in-situ residue management, awareness creation, and promotion of ex-situ technologies through coordinated action by central and state governments [21]. The policy provides central financial assistance for procuring machinery like Happy Seeder, Super SMS, rotavators, and zero till seed drills. It promotes the establishment of Custom Hiring Centres (CHCs) to enable smallholders to access machinery. The NPMCR outlines a multi-dimensional policy architecture focused on four core objectives: (i) prevention of environmental degradation through in-situ management; (ii) promotion of diversified uses for crop residues including fodder, compost, ethanol, and biomass power; (iii) capacity building through extension services; and (iv) enactment of legislative frameworks to curb open burning. The policy also supports public-private partnerships (PPPs) for valorization of biomass and recommends the institutionalization of adaptive research for developing low-cost, climate-resilient implements [21]. However, the policy has limited reach in eastern and southern India where non-rice residues dominate, and machine compatibility is poor [26].

6.1.2 Crop Residue Management (CRM) Scheme (2018–present)

Launched under the National Mission on Sustainable Agriculture (NMSA), this scheme specifically targets Punjab, Haryana, Uttar Pradesh, and NCT Delhi, states responsible for over 70% of stubble burning incidents. As of 2021, ₹1,730 crores had been allocated for machinery procurement, CHC establishment, and extension activities [3]. The scheme has led to the distribution of over 50,000 machines, yet studies show underutilization due to poor training and service delivery gaps [66]. Since the CRM Scheme's launch, cumulative funding of over ₹3,138 crores has been allocated to high-burden states. Punjab received ₹1,426.45 crore, Haryana ₹916.71 crore, and Uttar Pradesh ₹713.67 crore. Despite the distribution of over 2.42 lakh machines, field-level adoption remains uneven [3].

6.1.3 Other Relevant Policies and Missions

The National Bio-Energy Mission and SATAT (Sustainable Alternative Towards Affordable Transportation) promote the use of agri-residues in bio-CNG and bioethanol production [55]. The National Action Plan on Climate Change (NAPCC) and State Action Plans on Climate Change (SAPCCs) integrate residue management into broader climate-resilient agriculture strategies [12]. FAME II (Faster Adoption of Electric Vehicles) indirectly supports air quality goals but lacks integration with agricultural emission reductions [55].

6.1.4 PPP in Residue Supply Chains

The Ministry has adopted a Public-Private Partnership (PPP) model to strengthen ex-situ residue value chains. This model incorporates a tripartite cost-sharing structure, 65% by government, 25% by industry, and 10% by farmers or aggregators. Escrow accounts are mandated for transparency, and long-term procurement agreements between aggregators and industries are promoted [3]. The model seeks to operationalize decentralized collection, preprocessing, and biomass linkage to industry and energy users.

6.2 State-Level Responses and Innovations

6.2.1 Punjab: Integrated Interventions

The Punjab Pollution Control Board (PPCB) and Punjab Agricultural University (PAU) have scaled Happy Seeder usage and piloted the PUSA Decomposer with IARI [65]. The state's geo-tagging initiative for CRM machines has improved monitoring and deployment.

6.2.2 Haryana: Digital Monitoring and Decomposer Use

Haryana has deployed remote sensing tools to track burning incidents and applied the PUSA Decomposer on over 50,000 acres. Awareness campaigns have been organized with the Haryana Space Applications Centre [14], [65].

6.2.3 Uttar Pradesh: Mixed Performance

Despite being a high-burden state, implementation in Uttar Pradesh is hindered by weak fund utilization, poor extension infrastructure, and fragmented institutional support [66].

6.3 Institutional Challenges in Policy Execution

6.3.1 Inter-Ministerial Fragmentation

Residue management overlaps with the responsibilities of MoAFW, MoEFCC, MNRE, and state-level agencies, causing duplication and poor accountability. The NPMCR identifies the lack of a unified authority as a key issue and recommends state-level legislation and nodal agency designations to streamline enforcement [3].

6.3.2 Poor Farmer Engagement and Awareness

Many farmers remain unaware of schemes, subsidy procedures, or the proper use of machines. Low digital literacy prevents them from accessing DBT portals and government e-services [7].

6.3.3 Lack of Monitoring and Impact Evaluation

Existing programs often lack monitoring and evaluation frameworks to assess their long-term impact on yields, air quality, or carbon sequestration [10], [76].

6.4 International Case Studies and Lessons

6.4.1 China's Straw Return Program

China mandates straw incorporation into soils with strong subsidy backing and extension networks. As a result, over 85% of agricultural residues are managed sustainably [77].

6.4.2 European Union: Bioeconomy and Circularity

EU frameworks incentivize biomass valorization via funding, PPPs, and carbon credits under the Common Agricultural Policy (EU CAP) [76].

6.4.3 US Conservation Stewardship Program (CSP)

The NRCS incentivizes residue retention and conservation tillage through performance-based payments, coupled with technical assistance.

6.5 Role of Non-Governmental Actors

Non-governmental organizations (NGOs) have played a critical role in catalyzing awareness, piloting solutions, and advocating for policy reforms related to crop residue management. Organizations such as The Energy and

Resources Institute (TERI), Development Alternatives, and Revival of Bharat Foundation have been instrumental in grassroots mobilization, conducting field demonstrations, and facilitating stakeholder dialogues [66]. The private sector has increasingly entered the space through innovations in biomass supply chain management and digital technologies. Companies like Biofuel Circle and Agri Services have developed platforms for biomass trading, machinery rentals, and precision agriculture solutions aimed at improving the accessibility and efficiency of sustainable practices [3]. Kisan Kraft and other Agri-tech startups are also contributing by developing affordable machinery tailored for smallholder use.
India's policy response to crop residue burning has evolved significantly over the past decade, transitioning from punitive frameworks to incentive-based, technology-driven interventions [3]. Despite this shift, challenges such as fragmented institutional ownership, limited outreach to small and marginal farmers, and inadequate monitoring persist. To achieve greater impact, India must:

- Foster convergence across ministries and departments.
- Embed residue management into broader frameworks like climate finance and agricultural insurance.
- Decentralize implementation through empowered Panchayati Raj Institutions and Farmer Producer Organizations.
- Shift from output-focused subsidies to outcome-based metrics linked to actual reduction in burning events.
- Use real-time tracking tools and remote sensing to validate interventions [77], Scale up public–private–community partnerships for market-led innovation.

Only by integrating these systemic enablers can residue management transition from a reactive measure to a long-term climate-resilient agricultural practice.

VII. CLIMATE CHANGE IMPERATIVES AND GLOBAL CONTEXT

Crop residue burning, while often framed as a local agricultural issue, has profound implications for global climate change mitigation, especially in the Global South. The open-field combustion of agricultural waste releases not only carbon dioxide (CO_2), but also methane (CH_4), nitrous oxide (N_2O), and short-lived climate pollutants such as black carbon, which significantly impact atmospheric warming [74]. These emissions contribute to both localized air quality deterioration and broader climate destabilization. India, having committed to reaching net-zero emissions by 2070 under the Paris Agreement framework, must prioritize residue management as a key mitigation strategy. Reducing stubble burning through in-situ conservation and bioenergy valorization aligns directly with India's Nationally Determined Contributions (NDCs), while also improving soil health, agricultural sustainability, and rural livelihoods [58].

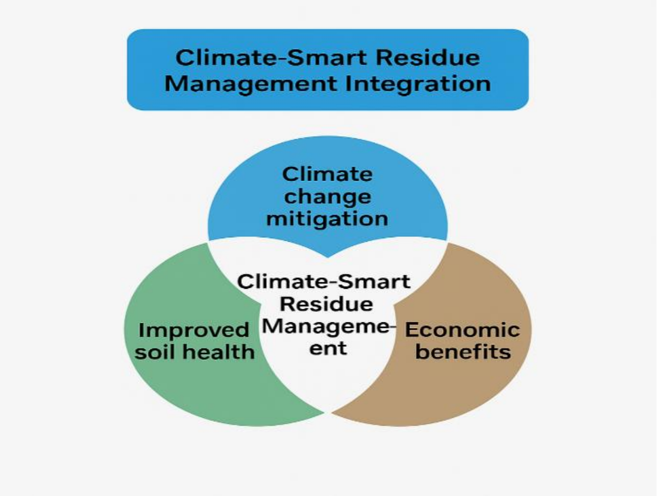

Figure 7: Climate-Smart Residue Management: Intersection of Agriculture, Climate, and Circularity

These pillars (as shown in figure 7) support an integrated framework for climate-resilient agriculture in India, as emphasized in the National Policy for Management of Crop Residues (NPMCR) and aligned with Sustainable Development Goals (SDGs) [3].

7.1 Contribution of Crop Residue Burning to GHG Emissions

India is the second-largest emitter of agricultural emissions globally, and open burning of crop residues constitutes a significant component of this burden. The combustion of crop residues emits large quantities of carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), the latter two having global warming potentials (GWP) of 28 and 265 times that of CO_2, respectively, over a 100-year time horizon [78] .

- Estimates suggest that crop residue burning in India contributes 15 to 20 million tonnes of CO_2-equivalent emissions annually [66].
- In addition, it releases black carbon, a potent SLCP, which not only contributes to regional warming but also accelerates Himalayan glacier melt by darkening snow albedo [75], [79].

The cyclical burning in the Indo-Gangetic Plain thus has implications that transcend regional boundaries, influencing South Asian monsoonal systems and exacerbating transboundary haze pollution [12].

7.2 Alignment with India's NDCs and Net-Zero Commitments

Under the Paris Agreement, India has committed to:

- Reduce the emissions intensity of GDP by 45% by 2030 (from 2005 levels),

- Achieve 50% cumulative electric power capacity from non-fossil fuel sources,
- Create additional carbon sinks of 2.5 to 3 billion tonnes of CO_2-equivalent through afforestation and sustainable land use.

While agriculture is currently excluded from direct mitigation targets, sustainable agricultural practices, including residue management, are integral to achieving these goals.

- Incorporating in-situ residue management, bioenergy substitution, and composting can significantly contribute to soil carbon sequestration and reduction of non-CO_2 GHGs.
- Policies such as the National Bio-Energy Mission, SATAT, and State Action Plans on Climate Change (SAPCCs) have begun integrating crop residues into the mitigation architecture, but the effort remains piecemeal [3], [55].

7.3 Relevance of IPCC Recommendations and Climate Models

The IPCC Special Report on Climate Change and Land (2019) underscores that sustainable land use practices, including integrated crop residue management, play a pivotal role in reducing emissions and enhancing resilience.

Key recommendations include:

- Reducing agricultural emissions through low-carbon residue handling,
- Adopting no-till and mulching practices to increase carbon sequestration,
- Utilizing biomass for renewable energy, provided lifecycle emissions remain below fossil benchmarks [58], [78]

Adoption of such practices aligns with AR6 Working Group III's pathways for limiting warming to below 2°C, where agriculture and land-use change represent 25–30% of the mitigation potential [80].

7.4 Integration into Climate-Smart Agriculture (CSA) Framework

Residue management is a key pillar of Climate-Smart Agriculture (CSA), which promotes the triple win of:

- Enhanced productivity,
- Increased resilience to climate shocks,
- Reduced GHG emissions [34], [81]. Practices such as Happy Seeder-based sowing, zero tillage, and biological decomposition contribute directly to CSA outcomes by:
- Improving water-use efficiency,
- Building climate-resilient soils,
- Reducing input use and fuel consumption.

Moreover, CSA approaches provide an opportunity to mainstream adaptation and mitigation co-benefits within India's broader agricultural strategy, especially under National Innovation on Climate Resilient Agriculture (NICRA) and the National Mission on Sustainable Agriculture (NMSA).

Quantifying soil carbon sequestration is crucial to validating the climate mitigation potential of sustainable residue management practices. Empirical studies suggest that conservation agriculture practices such as zero tillage with residue retention can enhance soil organic carbon (SOC) stocks by 0.3 to 1.2 Mg C ha^{-1} yr^{-1}, depending on climatic, edaphic, and management conditions [58]. Similarly, biochar application derived from paddy straw has shown long-term carbon stability, with sequestration potentials ranging from 0.7 to 1.0 Mg C ha^{-1} yr^{-1} in the Indo-Gangetic region [82]. The PUSA Decomposer also contributes indirectly by accelerating microbial biomass carbon accumulation, though its long-term SOC impact needs further validation. Integrating such sequestration estimates into India's Monitoring, Reporting, and Verification (MRV) frameworks would enable their monetization under voluntary carbon markets and reinforce their alignment with national climate targets [3].

7.5 Opportunities in Global Climate Finance and Carbon Markets

Residue management solutions have not yet been fully monetized through carbon finance or integrated into voluntary offset schemes. However, their potential is significant:

- In-situ retention and decomposition can be quantified in terms of soil carbon stock improvements, making them eligible under methodologies like Verra's VM0042 Improved Agricultural Land Management [55].
- Ex-situ valorization, particularly biochar production, offers durable carbon storage and is increasingly recognized in global climate finance platforms.

Integrating residue management into India's Long-Term Low Emissions Development Strategy (LT-LEDS) could attract public and private climate investment, particularly under Article 6.2 cooperative approaches and results-based finance frameworks [55]. Crop residue management must be understood not merely as an agricultural or environmental challenge, but as a strategic lever in India's climate policy architecture. The sector provides a high-impact, low-cost opportunity to address emissions from agriculture, enhance carbon sequestration, and build adaptive capacity. Aligning sustainable residue management practices with India's NDCs, IPCC recommendations, and climate-smart agricultural frameworks is imperative to achieving both national development objectives and global environmental commitments. Unlocking its potential, however, requires cross-sectoral policy integration, MRV (Measurement, Reporting, and Verification) mechanisms, and access to carbon and climate finance instruments [12], [66]. Circular Economy and Sustainable Development Integration

Recent developments include the integration of crop residue management within the broader framework of sustainable agriculture through schemes like PM-PRANAM (Programme for Restoration, Awareness, Nourishment and Amelioration of Mother Earth). Pilot initiatives involving blockchain-based residue traceability systems and residue-to-bioplastics programs have been initiated, promoting a circular economy approach. Public-private partnerships (PPPs) have become more prominent in establishing decentralized biomass supply chains and agro-industrial linkages [83].

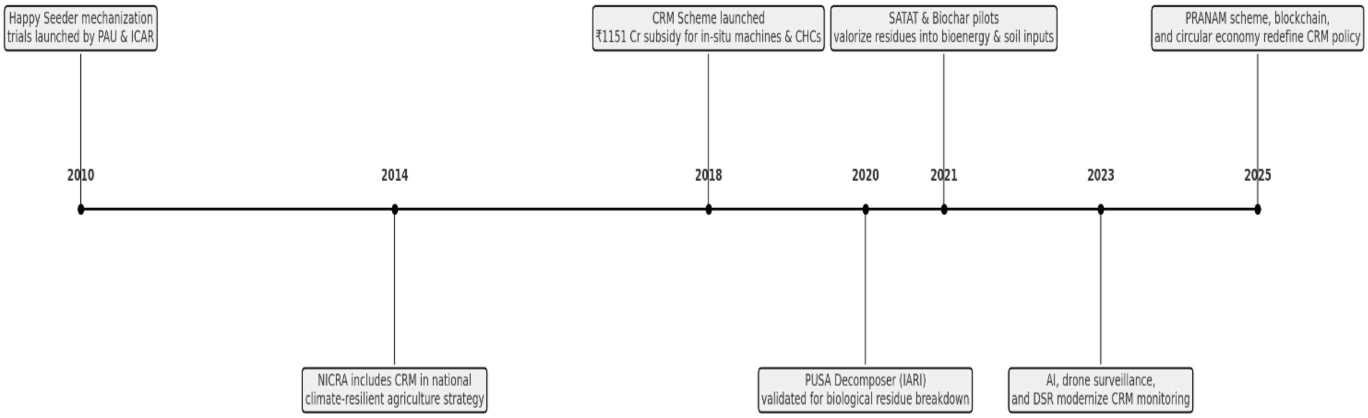

Figure 8: Strategic Timeline of Crop Residue Management in India (2010-2025)

The trajectory of crop residue management in India has evolved from localized mechanical interventions to an integrated policy and technological ecosystem as shown in figure 8 & 9. While initial efforts focused on mitigation through mechanization and penalties [40], the more recent paradigm emphasizes sustainability, value creation, and digital integration [66], [83]. Continued research, behavioral change among farmers, and scalable public-private collaboration remain vital for long-term success [7], [23]

VIII. FUTURE DIRECTIONS AND RESEARCH GAPS

While significant strides have been made in understanding and deploying alternatives to crop residue burning, several technological, institutional, and knowledge-based gaps persist. Furthermore, emerging global challenges, such as climate change, resource scarcity, and ecological degradation, call for the reinvention of crop residue as a resource within a circular, climate-resilient agricultural economy. This section outlines the key innovation pathways and identifies research voids that must be addressed to unlock the full potential of sustainable residue management in India.

Figure 9: Pathways for Adoption of Crop Residue Alternatives: From Pilot to Scale

8.1 Technological Innovations and Scaling Potential

8.1.1 Precision and Digital Technologies

There is growing scope to deploy remote sensing, IoT devices, AI-powered stubble detection, and GPS-based machinery coordination to improve monitoring, efficiency, and targeted interventions.

- Satellite-based burn tracking (e.g., NASA FIRMS, ISRO Bhuvan) has been used for enforcement, but integration into real-time advisory systems for farmers remains limited.

- Development of mobile platforms to connect farmers with custom hiring services, residue-based industries, and carbon markets could significantly scale adoption.

8.1.2 Bio-Innovation and Agroecological Approaches

Next-generation microbial formulations and biotechnological applications hold promise for faster, more efficient decomposition:

- Synthetic microbial consortia, customized for agro-climatic zones, could enhance decomposition efficacy.
- Research into mycelial degradation (fungal-based) systems and enzymatic pretreatments could improve lignocellulosic residue breakdown.
- Biochar production from residues can offer long-term carbon sequestration, improve soil structure, and serve as a soil amendment.

8.2 Systemic Integration and Business Model Development

8.2.1 Circular Economy Integration

Residue management should be embedded in sustainable agri-industrial symbiosis, enabling residue flows to sectors such as:

- Bioenergy (ethanol, briquettes, pellets),
- Bioplastics and biodegradable packaging,
- Construction materials (compressed straw panels, insulation boards).

This necessitates value chain mapping, logistics optimization, and private sector participation through PPP models.

8.2.2 Farmer-Centric Business Models

Scalable solutions require institutional innovations, such as:

- Decentralized biomass cooperatives,
- Village-level aggregators,
- Pay-per-use machinery rental platforms, integrated with credit and insurance products.

These models must be gender-sensitive, ensuring women farmers, often excluded from capital-intensive programs, benefit from training, employment, and inclusion in decision-making.

8.3 Policy, Finance, and Carbon Incentivization

8.3.1 Carbon Markets and Climate Finance

Despite their climate mitigation potential, sustainable residue practices are not yet widely included in India's carbon credit registry or voluntary offset schemes.

- Research is needed to establish MRV (Measurement, Reporting, and Verification) protocols for in-situ and ex-situ interventions.
- Climate-resilient farming incentives, potentially financed through Green Climate Fund (GCF) or voluntary markets, could catalyze adoption.

8.3.2 Integration with Rural Development and Climate Action

Residue management must be mainstreamed into existing programs, such as:

- MGNREGA, through composting pits and storage infrastructure construction;
- PM-KUSUM, linking farmers to bioenergy revenue streams;
- National Mission on Sustainable Agriculture (NMSA), aligning with conservation agriculture goals.

8.4 Research Gaps in Social, Environmental, and Economic Domains

8.4.1 Longitudinal Impact Assessments

Few studies have explored the long-term impacts of sustainable residue management on:

- Soil nutrient dynamics,
- Farm economics (cost-benefit analysis over multiple crop cycles),
- Crop yield stability and pest ecology.

This limits evidence-based policy-making and farmer trust.

8.4.2 Socioeconomic and Behavioural Research

Further research is needed on:

- Adoption behavior across socio-economic groups,
- Cultural barriers, gendered dimensions, and intergenerational knowledge transfer,
- Farmer perceptions of climate risk and its role in adoption decisions.

8.4.3 Regional and Crop-Specific Data

Current residue management research is skewed toward rice-wheat systems of Punjab and Haryana. There is a dearth of:

- Residue characterization for coarse cereals, pulses, and oilseeds,
- Agro-climatic zone–specific technology recommendations,
- Adoption and impact studies from eastern, southern, and central India.

The transition to sustainable residue management in India hinges on addressing deep-rooted systemic and scientific challenges. Future efforts must focus on developing region-specific, farmer-centric, and economically viable solutions, enabled by cutting-edge digital tools, bio-innovations, and institutional reform. Bridging research gaps, particularly around long-term environmental outcomes, socioeconomic behavior, and carbon monetization, is essential for evidence-driven policies. A future-oriented, transdisciplinary approach, merging science, policy, and community engagement, can transform crop residue from an ecological burden into a climate-smart asset.

IX. DISCUSSION

The pervasive practice of crop residue burning in India, particularly in the Indo-Gangetic Plain (IGP), continues to undermine national objectives related to sustainable agriculture, air quality improvement, and climate change mitigation [11], [13], [66], [74]. Despite the availability of a diversified portfolio of sustainable alternatives, the actual on-ground transition remains inconsistent and slow. The analysis presented in this paper reveals a multidimensional problem that spans across agronomic feasibility, socio-economic constraints, institutional fragmentation, and behavioural inertia [7]. Among the various residue management strategies evaluated, in-situ methods such as the Happy Seeder, Zero-Tillage with Mulch, and PUSA Decomposer demonstrate the highest potential for integration into smallholder farming systems [40]. These practices contribute to soil health regeneration, microbial diversity, and GHG mitigation, while reducing input costs over time. Empirical studies have shown that in-situ retention improves soil organic carbon, moisture retention, and weed suppression, leading to long-term yield stability [58], [84]. PUSA Decomposer represents a scalable, low-cost, and non-mechanized solution with a short decomposition cycle, offering a viable entry point for resource-poor farmers. However, its effectiveness is climate-dependent, with reduced microbial efficiency under low temperatures and suboptimal soil moisture [7]. While these technologies exhibit agronomic robustness, their adoption is hindered by equipment cost barriers, dependency on high-horsepower tractors, and limited availability of Custom Hiring Centres (CHCs) in non-IGP states [3]. Additionally, farmer training on technical usage, especially for herbicide management under zero-till systems, remains insufficient [46]. Equitable scalability requires a parallel investment in rural service ecosystems, digital rental platforms, and region-specific extension services.

Ex-situ biomass utilization strategies, such as briquetting, pelletization, biomass-based power generation, and bio-CNG plants, have gained policy traction under schemes like SATAT and the National Bio-Energy Mission [55]. These pathways align with India’s renewable energy targets and offer dual benefits: waste valorization and fossil fuel substitution [3]. The NTPC biomass co-firing model, for instance, showcases the integration of agri-residue pellets into thermal power plants [76]. However, these models are logistics-intensive, requiring aggregation hubs, drying yards, transportation networks, and quality standards. Additionally, continuous biomass removal may cause nutrient mining unless supplemented with compost or biochar [58], [82]. Adoption must be guided by nutrient budgeting frameworks, which are largely absent from state CRM plans [38]

The fragmented institutional landscape, spanning MoAFW, MoEFCC, MNRE, and state governments, creates implementation delays and weak coordination [76]. Despite progressive policies like NPMCR and the CRM Scheme under NMSA, over 80% of machinery procurement and fund utilization remains concentrated in Punjab and Haryana [21]. States with rising residue issues, such as Maharashtra, Tamil Nadu, and Odisha, lack state-specific action plans, access to CHCs, and localized CRM programs. Weak M&E frameworks, insufficient geo-tagging, and limited digital literacy among farmers also hamper delivery. A mission-mode nodal agency with multi-ministerial participation is needed for convergence and accountability. Crop residue burning contributes up to 20 million tonnes of CO_2-equivalent emissions annually. Yet CRM remains absent from India's carbon finance mechanisms and voluntary offset frameworks. Practices such as biochar production, in-situ mulching, and PUSA Decomposer use can generate verifiable mitigation benefits. However, lack of MRV tools, baselines, and certified protocols (e.g., under Verra or CDM) limits inclusion in carbon markets. India’s upcoming Voluntary Carbon Market Framework and LT-LEDS strategy offer a platform to embed CRM as a cost-effective, farmer-led mitigation instrument. CRM programs and research are disproportionately focused on the IGP, especially during Delhi's pollution crises, while eastern and southern states remain neglected. Residues from crops like sugarcane, cotton, and coarse cereals, prevalent in Tamil Nadu, Maharashtra, and Chhattisgarh, are under-researched and excluded from major policy interventions. This spatial bias results in poor adoption outside Punjab and Haryana, with tools unsuited to regional needs. Reorientation is needed through agro-ecological zoning, region-specific pilots, and diversified financial support.

Burning persists not only due to technical gaps but also social norms and structural inequities. Farmers often perceive burning as fast and cost-free, particularly where penalties are absent and training is limited. Women, who form a third of the agri-labor force, are mostly excluded from CRM decisions and training. Labor-intensive methods like composting are discouraged due to migration and the rising opportunity cost of farm labor. Behavioural change strategies, including SHG-led hiring, self-certification, and Gram Sabha validation, can help integrate gender-inclusive, scalable interventions.

X. CONCLUSION AND POLICY RECOMMENDATIONS

10.1 Conclusion

Crop residue burning remains one of the most visible yet structurally entrenched challenges in Indian agriculture. Despite a wide array of available technological, biological, and circular economy solutions, large-scale transition to sustainable residue management remains constrained by economic barriers, institutional fragmentation, regional disparities, and behavioural inertia. This review has critically examined the environmental, economic, and climate consequences of residue burning, assessed the comparative effectiveness of alternative practices, and identified the barriers impeding their adoption. It has also mapped the evolving policy landscape, from central government schemes to state-level innovations, and aligned these with India's climate change imperatives and sustainable development commitments. The central insight emerging from this study is that technical solutions alone are insufficient. Sustainable residue management must be supported by systemic policy integration, targeted financial instruments, farmer-centric models, and inclusive governance mechanisms. Furthermore, climate change provides a compelling framework to reposition residue management not only as a pollution control measure but also as a carbon mitigation strategy, rural livelihood opportunity, and pathway to soil regeneration.

10.2 Policy and Implementation Recommendations

1. Adopt a Region-Specific, Crop-Centric Strategy

- Develop differentiated action plans tailored to regional cropping patterns, residue types, and infrastructure availability.
- Move beyond the rice-wheat belt to address burning in cotton, sugarcane, and coarse cereals through localized solutions.

2. Strengthen Custom Hiring and Cooperative Access Models

- Expand and digitalize Custom Hiring Centres (CHCs) and incentivize Farmer Producer Organizations (FPOs) to manage shared machinery fleets.
- Promote pay-per-use platforms and app-based rental systems that allow small and marginal farmers to access equipment affordably.

3. Integrate Crop Residue Management into Climate Finance Mechanisms

- Establish MRV (Monitoring, Reporting, Verification) frameworks for in-situ retention and biochar application.
- Enable farmer access to carbon markets through residue-based carbon credits, especially under India’s Voluntary Carbon Market Framework.
- Mainstream residue management under SAPCCs, LT-LEDS, and Green Climate Fund (GCF) proposals.

4. Promote Research and Innovation on Bio-Based Technologies

- Support R&D in next-gen microbial decomposers, mycelial solutions, AI-enabled stubble detection, and low-cost bioenergy conversion technologies.
- Incentivize private sector and academic collaboration for patenting, piloting, and scaling climate-smart innovations.

5. Integrate Residue Management into Rural Development and Employment Programs

- Leverage MGNREGA for building composting infrastructure and supporting biomass aggregation systems at the village level.
- Encourage training of rural youth and women in residue processing units, creating new livelihood streams.

6. Create Behavioural and Institutional Change Through Awareness and Extension

- Launch regionally tailored IEC (Information, Education, Communication) campaigns to address myths and promote the long-term benefits of sustainable practices.
- Strengthen the capacity of extension workers, including Krishi Vigyan Kendras (KVKs), to provide technical guidance on alternative residue management.

7. Build an Integrated Governance Framework

- Establish a National Residue Management Mission under the joint stewardship of the Ministry of Agriculture, MoEFCC, and MNRE with clear targets, timelines, and state-level accountability mechanisms.
- Enable real-time monitoring through remote sensing, geo-tagging of equipment, and public dashboards to improve transparency and enforcement.

10.3 Research Recommendations

- Conduct longitudinal field trials to evaluate the agronomic, economic, and emissions impacts of different residue management methods over time.
- Expand data collection in under-researched regions (e.g., Odisha, Maharashtra, Tamil Nadu) to inform national strategies.
- Investigate gendered dimensions, farmer psychology, and labor dynamics in adoption behaviour, especially in contexts of migration and climate stress.

Transforming crop residue from a waste liability into a resource opportunity requires a multidimensional shift, technological, institutional, and ideological. As India marches toward its net-zero goal, sustainable residue management stands out as a low-hanging fruit with the potential to deliver co-benefits in climate mitigation, soil health, rural employment, and public health. Unlocking this potential will require a collaborative, inclusive, and future-oriented policy ecosystem, one that empowers farmers, protects the environment, and secures sustainable livelihoods for generations to come.

XI. REFERENCES

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