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Advanced Machinery for Crop Residue Management in India: Challenges and Opportunities

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Abstract
India, one of the world's largest agricultural producers, generates millions of tons of crop residue annually. A significant portion remains unutilized and is often burned in the open, particularly in states like Punjab, Haryana, and Uttar Pradesh. This practice contributes heavily to air pollution, greenhouse gas emissions, and soil degradation. Despite the availability of technologies such as balers, straw reapers, and shredders, their widespread adoption remains limited.

This study explores the current status, challenges, and opportunities in promoting mechanized crop residue management across India. Using a qualitative methodology, 25 in-depth interviews were conducted with policymakers, scientists, machinery manufacturers, sustainability experts, and field-level implementers. The research identifies key barriers such as high machinery costs, limited access to financing, lack of awareness, and insufficient training. Although government subsidies and schemes exist to promote mechanization, issues like delayed disbursement, low awareness, and weak last-mile implementation dilute their effectiveness.

Findings also indicate that behavioral inertia and absence of localized capacity building contribute to the persistence of residue burning. Many small and marginal farmers still choose burning due to habit, convenience, and lack of viable alternatives. However, some successful public-private partnerships demonstrate potential, where crop residue is processed for biomass energy and other value-added uses.

Logistical challenges—such as transporting and storing biomass—remain major bottlenecks. The study concludes that while technology exists, systemic gaps in policy, finance, awareness, and infrastructure hinder adoption. It recommends a multi-stakeholder approach involving coordinated policy reform, targeted training, innovative financing, and stronger private sector involvement. With the right support mechanisms, India can shift from residue burning to sustainable, value-driven residue utilization—benefiting both farmers and the environment.

Key Words- Crop residue, Stubble burning, Machinery, Sustainability, Agriculture, Biomass, Awareness, Adoption, Technology, Policy, Baling, Utilization, Environment

1 | Introduction

Crop residue management (CRM) is a pressing agricultural challenge in India, particularly in the rice-wheat cropping systems of Punjab, Haryana, and Uttar Pradesh, where the widespread burning of paddy straw contributes to severe air pollution, soil degradation, and public health risks (Singh et al., 2020). The practice of residue burning persists due to the short turnaround time between harvesting and sowing, high labor costs, and a lack of economically viable alternatives (Jain et al., 2019). Despite government interventions promoting mechanized residue incorporation and ex-situ utilization, adoption remains low due to logistical, financial, and awareness-related barriers (Kumar et al., 2021).

Qualitative survey data highlights the complexities of CRM, revealing that while in-situ methods (e.g., happy seeders, mulching) improve soil health, they also pose challenges such as pest proliferation and nutrient immobilization (Shyamsundar et al., 2022). Ex-situ solutions, such as biomass baling for bioenergy or fodder, face hurdles like high capital costs and underdeveloped supply chains. Government schemes, including subsidies for CRM machinery and financial incentives for residue collection, have had limited impact due to delayed implementation and inadequate outreach (Singh et al., 2020).

Emerging technologies, such as advanced balers and biomass converters, offer promising solutions but require stronger public-private collaboration to enhance affordability and accessibility. Behavioral change among farmers hinges on financial incentives, training, and community-driven initiatives, as demonstrated by successful models like Punjab's M/s XXEL Ltd., which links residue management with economic benefits (Jain et al., 2019). Motivational strategies, including performance-based incentives, carbon credit mechanisms, and corporate social responsibility (CSR) funding, are seen as crucial for encouraging sustainable practices (Jain et al., 2019). Grassroots engagement through farmer training programs and demonstration plots can further build confidence in alternative CRM methods. Successful case studies, such as New Holland's baler deployment in Punjab and community-led biomass collection initiatives in South India, demonstrate the feasibility of scalable solutions (Kumar et al., 2021). However, experts emphasize the need for stronger policy coordination—possibly through a dedicated Ministry of Bio-Energy—and digital platforms for knowledge sharing and equipment rentals.

This paper examines the current challenges, policy gaps, and technological opportunities in CRM, emphasizing the need for integrated strategies to transition toward sustainable agricultural practices. Qualitative insights from 25 professionals—spanning academia, agricultural machinery manufacturers, policymakers, and field experts—reveal a multi-dimensional perspective on CRM. While mechanized solutions like balers, shredders, and happy seeders have gained traction through government subsidies (Kumar et al., 2021), their adoption remains limited due to high capital costs, operational complexity, and insufficient local service infrastructure (Shyamsundar et al., 2022). Government initiatives, such as the promotion of in-situ residue incorporation and Custom Hiring Centres (CHCs), have shown moderate success but suffer from fragmented implementation and inadequate farmer training. Experts suggest that more targeted approaches—such as decentralized palletisation units and behaviour change campaigns—could enhance adoption rates.

The transformative potential of agricultural technology is widely acknowledged, with innovations like high-density balers and torrefaction reactors offering avenues to convert crop residues into biofuels, compost, and fodder (Singh et al., 2020). However, challenges such as seasonal demand, lack of skilled labour, and weak market linkages hinder scalability. Public-private partnerships (PPPs), custom hiring models, and government-backed machinery clusters are proposed as solutions to improve accessibility and affordability. While advanced machinery presents a viable pathway for sustainable CRM, its success depends on a holistic approach integrating policy coherence, financial incentives, and farmer-centric outreach. This study underscores the importance of systemic interventions to transition India's agricultural sector toward environmentally sound residue management practices.

2 | Literature Review

Crop residue burning is a significant environmental and agricultural challenge in India, particularly in the rice-wheat cropping systems of Punjab, Haryana, and Uttar Pradesh. Despite government interventions and technological advancements, farmers continue to burn residues due to economic constraints, labour shortages, and lack of viable alternatives. This literature review synthesizes findings from multiple studies to analyse the determinants of farmers' adoption of sustainable residue management practices, the effectiveness of policy interventions, and the role of technology in mitigating environmental impacts.

Binswanger and Rosenzweig (1986) highlight how farmers' production decisions are influenced by both behavioural and material factors . In the context of crop residue management, farmers often prioritize short-term economic gains over long-term environmental benefits due to financial constraints. The study suggests that small landholders, in particular, are more likely to burn residues because they lack access to capital for machinery or alternative disposal methods. Similarly, Foster and Rosenzweig (1995, 1996) emphasize the role of human capital and learning in technology adoption. Their research shows that farmers who observe the benefits of residue retention (e.g., improved soil health) from peers are more likely to adopt sustainable practices. However, in India, the rapid transition between rice and wheat cropping seasons leaves little time for learning and experimentation, reinforcing reliance on burning.

Binswanger et al. (1993) examine how infrastructure and financial institutions shape agricultural productivity. Their findings suggest that poor rural infrastructure—such as inadequate storage, transportation, and processing facilities—limits the feasibility of ex-situ residue management (e.g., baling and biomass utilization). Without efficient supply chains, farmers find it economically unviable to collect and sell residues, leading to burning. Kumar and Joshi (2013, 2015) corroborate this in their case studies from Punjab, where farmers cite high transportation costs and lack of biomass markets as key reasons for residue burning. Their research highlights the need for government subsidies and private-sector involvement to develop residue-based industries.

Jain et al. (2014) quantify the severe air pollution caused by crop residue burning, particularly in northern India. Their study estimates that burning releases large amounts of particulate matter (PM2.5 and PM10), carbon monoxide (CO), and greenhouse gases (GHGs), contributing to Delhi's annual smog crisis. The economic cost of health impacts from burning-related air pollution is substantial, further justifying policy interventions. Pathak et al. (2010) discuss how residue burning exacerbates climate change by releasing methane (CH_4) and nitrous oxide (N_2O), both potent GHGs. They argue that in-situ residue management (e.g., mulching, incorporation) could reduce emissions while improving soil carbon sequestration.

Singh et al. (2010) and Yadav & Bhattacharyya (2014) demonstrate that residue retention enhances soil organic matter, water retention, and microbial activity. However, farmers in Punjab and Haryana remain skeptical due to perceived risks of pest infestations and delayed sowing. Mandal & Maity (2013) find that farmer education and demonstrations are crucial to changing these perceptions. Pannu (2015) evaluates Punjab's subsidy schemes and finds that while adoption has increased, delays in disbursement and high upfront costs remain barriers. The National Academy of Agricultural Sciences (NAAS, 2017) recommends expanding Custom Hiring Centres (CHCs) to improve smallholder access. The Supreme Court-mandated incentive of ₹100 per quintal of residue (as reported in Kumar et al., 2015) has had mixed success. While some farmers shifted to mechanical solutions, others continued burning due to delayed payments. Lohan et al. (2018) argue that stricter enforcement of burning bans, combined with assured compensation, is necessary.

Sidhu & Beri (2005) document its success in Punjab, showing yield improvements and reduced fuel use. However, Foster & Rosenzweig (2010) note that adoption remains low due to high machinery costs and lack of skilled operators. Ex-situ Technologies (Biomass Energy, Industrial Use)-Ex-situ methods, such as converting residues into biofuel or industrial raw materials, face logistical hurdles. Goyal (2010) highlights how ITC's e-Choupal initiative improved market linkages for crop residues, but scaling such models requires stronger public-private partnerships.

Comparative Insights from Global Studies-Lessons from Africa and South Asia Knowler & Bradshaw (2007) review conservation agriculture adoption in Africa, emphasizing that farmer training and peer networks are critical. Similarly, Deressa et al. (2009) find that climate adaptation strategies in Ethiopia succeeded only when tailored to local conditions. Aker (2011) and Aubert et al. (2012) discuss how mobile-based extension services (e.g., weather alerts, residue management tips) can enhance adoption. However, as seen in India's CHC app, digital tools alone are insufficient without on-ground support.

The literature underscores that sustainable residue management requires a multi-pronged approach, Strengthening Subsidy Systems: Ensure timely disbursement and expand CHCs, Developing Biomass Markets: Incentivize industries to procure residues at fair prices, Farmer Education: Conduct demonstrations to showcase long-term benefits of in-situ methods, Public-Private Partnerships: Scale up initiatives like e-Choupal for better market linkages, Stricter Enforcement: Penalize burning while offering viable alternatives. Hence the current research is attempting to explore behavioural nudges (e.g., carbon credits) and decentralized biomass processing units to make residue management economically viable for smallholders.

3 | Research Methodology

This study employs a qualitative research approach to examine the perceptions, challenges, and recommendations of stakeholders on the adoption of advanced machinery for agricultural residue management. Qualitative methods are ideal for capturing nuanced opinions and contextual barriers (Creswell & Poth, 2018). Data was collected via a qualitative survey administered to 25 stakeholders—comprising agri-engineers, policymakers, and farmers—to ensure diverse perspectives. The study used an Exploratory qualitative study approach which focuses on understanding "why" and "how" stakeholders perceive residue management machinery. Semi-structured survey: Open-ended questions allowed detailed responses (see *Appendix for sample questions*). Rationale for Qualitative Methods, Depth: Captures subjective experiences (e.g., farmers' practical challenges), Diversity: Contrasts viewpoints across stakeholder groups. Flexibility-Permits emergent themes (e.g., cost vs. policy bottlenecks). Purposive sampling ensured representation of key stakeholders, Farmers (12 participants): Direct end-users of machinery, Agri-engineers (8 participants): Technical experts, Policymakers (5 participants): Regulatory/implementation influencers. Stakeholders were contacted via agricultural cooperatives, professional networks, and government directories. Ethics: Anonymity was ensured; responses were recorded in Excel without identifiers. Each interaction took 25–40 minutes (self-administered/interview-based). The inputs from experts were sought on the key points such as Perceptions of advanced machinery (e.g., "How effective do you find current residue management machines?"). Barriers (e.g., "What limits adoption in your region?"). Solutions (e.g., "What policy/technical changes would help?"). The data is analysed using thematic Analysis.

SI No	Profile	Years of Experience
R1	Agri Professional	Over 25 years of experience
R2	Agri Industrialist	Selling Agri Machines and Tractors for 25 years
R3	Agri Professional	Agri Machine manufacturing, 30+ years experience
R4	Academics	Over 30 years of academic experience
R5	Agri Govt. Officer	Over 40 years in Punjab Agri Department
R6	Academics	30 years of experience in Agri Machinery
R7	Academics	30 years of experience in Agri Machinery
R8	Academics	Over 20 years of experience
R9	Large Farmer	Farming 6000 acres in Punjab
R10	Agri Professional	28 years of experience
R11	Agri Professional	Over 30 years of experience
R12	Agri Govt. Officer	35 years of experience in Agri Equipment Testing
R13	Agri Professional	35 years of experience
R14	Agri Professional	30 years of experience
R15	Agri Professional	30 years of experience
R16	Agri Professional	30 years of experience
R17	Agri Professional	30 years of experience
R18	Agri Professional	30 years of experience
R19	Agri Professional	35 years of experience
R20	Agri Professional	20 years of experience
R21	Agri Govt. Officer	35 years of experience
R22	Academics	25 years of experience

R23	Academics	30 years of academic experience
R24	Agri Professional	22 years of experience
R25	Agri Industrialist	35 years of experience in Agri Machinery

Table 1 – Profile of the respondents

4 | Results

Software: Excel was used for manual coding; quotes were tagged by stakeholder type.

Example Theme Output:

Theme	Stakeholder	Representative Quote
Cost Barriers	Farmers	*"Even with subsidies, the machine is 3x my yearly income."*
Tech Complexity	Agri-engineers	*"Operators lack skills to troubleshoot IoT systems."*

5 | Current Practices in Crop Residue Management

In-Situ Management: Techniques and Challenges-In-situ methods involve retaining or incorporating crop residues into the soil, offering agronomic benefits such as improved soil organic matter (SOM) and moisture retention. Key Technologies-Happy Seeder, Mechanism: Directly sows wheat into paddy stubble without burning, Pros: Reduces burning, enhances soil health, Cons: Requires high-horsepower tractors (50+ HP), which small farmers often lack, Expert Insight: *"Farmers fear yield loss due to pests in retained straw"* (Dr. Sidhu, PAU).

Rotavator: Mechanism: Mixes residue into the soil, Pros: Fast operation (2–3 acres/day), Cons: High fuel consumption (₹800–1,000/acre), Expert Insight: *"Small farmers cannot afford rentals; ownership is rare"* (Sachin Kapur, Jalandhar),.

Limitations of In-Situ Methods-Decomposition Delays: In cooler climates, residue takes longer to decompose, delaying sowing. Pest Proliferation: Improperly managed residue can harbor pests like termites. Ex-Situ Management: Opportunities and Barriers-Ex-situ methods involve removing residue from fields for alternative uses, such as bioenergy, fodder, or industrial raw material. Key Technologies-Balers-Mechanism: Compresses straw into bales for easy transport, Pros: Generates income (₹5–7/kg of bales), Cons: High capital cost (₹12–15 lakh), storage challenges, Expert Insight: *"No storage facilities force farmers to sell at throwaway prices"* (Barjinder Singh, CNH).

Pellet Mills-Mechanism: Converts straw into fuel pellets, Pros: Alternative to coal in industries, Cons: Seasonal demand fluctuations, Expert Insight: *"Biomass plants are 100 km away; transport costs erode profits"* (Rajan Agarwal, AGI Milltec). Supply Chain Challenges-

Fragmented Landholdings: Small farms (1–2 acres) make mechanized collection inefficient, Transport Costs: ₹3–5/km for bales vs. ₹0.5/km for coal. Case Study: Punjab's New Holland Balers (80 units sold in 2023) succeeded due to group leasing models among farmers.

Policy Landscape and Implementation Gaps, Government Initiatives, Subsidies on CRM Machinery, 50% subsidy for individual farmers, 80% for farmer groups, Issue: Delays in disbursement (6+ months). Custom Hiring Centres (CHCs), Provide rental access to machinery, Issue: Lack of repair services in rural areas, CHC Farm Machinery App, Connects farmers to nearby CHCs, Issue: Low digital literacy among farmers.

Expert Recommendations for Policy Improvement-Pre-Season Subsidy Disbursal: Ensure funds are released by September for kharif harvest, Biomass Banks: Establish storage hubs (like FCI godowns) to stabilize prices, Carbon Credits: Reward farmers (₹1,000/acre) for in-situ residue retention (Dr. Bector, PAU).

Barriers to Adoption of Advanced Machinery-Economic Barriers, High Capital Costs: Balers (₹12–15 lakh), Happy Seeders (₹1.5 lakh). Operational Costs: Fuel, maintenance, and labor. Technical Barriers-Power Requirements: 45+ HP tractors (owned by only 15% of Punjab farmers). Lack of Skilled Operators: *"No mechanics in 60% of villages"* (Gaurav Sood, TAFE). 3.3 Logistical Barriers-Storage: *"Moisture ruins bales in 10 days"* (Jang Bahadur, Farmer).Transport: High costs and poor rural road connectivity.

Six-Point Action Plan for Sustainable CRM-Subsidize Local Manufacturing: Reduce baler costs by 30% (China model). Expand CHCs with Repair Units: Train rural youth as technicians. Biomass Pricing Policy: MSP for straw (₹2/kg) to prevent fires. Industry Partnerships: Mandate 10% biomass co-firing in power plants (NTPC model). Awareness Drives: Farmer field schools (PAU's "No Burn Campaign" reduced fires by 41%). R&D: Develop low-power residue shredders (<30 HP).The transition to mechanized CRM in India requires addressing cost, skill, and supply chain gaps. While policies like subsidies and CHCs are steps forward, sustained financing, industry collaboration, and farmer education are critical. Future research should explore AI-based residue mapping to optimize collection routes

6 | Discussion

The findings from the qualitative survey of 25 professionals across the agricultural machinery, policy, and environmental sectors reveal a complex interplay of technological, economic, and behavioural factors influencing the adoption of advanced machinery for crop residue collection in India. The responses collectively underscore a growing awareness of mechanized solutions such as balers, rakes, and straw choppers, particularly in regions like Punjab and Haryana, where policy incentives and large-scale demonstrations have been conducted. However, accessibility to these technologies remains uneven due to high upfront costs, lack of financing options, and limited custom hiring centres in rural belts. A recurring theme across the responses is the low level of technical training and operational knowledge among farmers, which leads to underutilization of machinery even when available. Government schemes like the CRM (Crop Residue Management) initiative have created some impact, yet professionals report inefficiencies in subsidy disbursement, a lack of follow-up, and weak linkages between research bodies and on-ground implementation. Some experts also pointed to logistical challenges in collecting, transporting, and aggregating biomass for industrial use, especially torrefied pellet manufacturing. Environmental concerns due to stubble burning persist despite machinery availability, reflecting a behavioural gap that policy alone cannot fill. Respondents emphasized the role of private players, cooperatives, and public-private partnerships to strengthen last-mile delivery of services. There is consensus that while technology is not a limitation, its deployment and adoption suffer due to systemic gaps in training, infrastructure, and coordination. The study also highlighted encouraging trends, including pilot projects that are showing promise in improving biomass supply chains and creating alternate income streams for farmers. Overall, the qualitative data suggest that a multi-stakeholder approach combining technology access, farmer education, supportive policy, and entrepreneurial investment is essential to scale the sustainable use of crop residue collection machinery in India.

7 | Conclusion

The research aimed to investigate the role, challenges, and opportunities associated with the use of advanced machinery for crop residue collection in India, drawing on the insights from a qualitative survey of 25 professionals. The study has highlighted that while India possesses the technological means to significantly reduce stubble burning and repurpose agricultural waste, the journey from innovation to impactful implementation is still incomplete.

One of the most critical insights from the study is that availability of machinery is not the primary barrier—rather, it is the accessibility, affordability, and appropriate usage of such equipment that determine its effectiveness. While machines like balers, straw reapers, and rakes are increasingly being adopted in certain geographies, their penetration in marginal and smallholder farming remains low. Factors such as high capital cost, lack of financing models, absence of trained operators, and fragmented ownership models hinder widespread adoption.

The qualitative feedback also pointed toward the need for more robust institutional support. Many respondents highlighted that while the government has introduced commendable schemes such as subsidies for machinery and crop residue management programs, their effectiveness is diluted by bureaucratic delays, inconsistent policy execution, and lack of awareness among end users. Moreover, post-harvest residue logistics—such as storage, transportation, and aggregation—pose significant bottlenecks to creating an economically viable biomass value chain.

Environmental awareness is growing, but behavioural inertia and short-term economic pressures often lead farmers to resort to stubble burning despite available alternatives. The solution, therefore, lies not just in promoting machinery, but in building a holistic ecosystem involving farmer training, reliable access to custom hiring centres, localized demonstration projects, and sustainable end-markets for collected biomass—such as biomass pellets for power plants.

Encouragingly, a few successful models are emerging, where private enterprises, government bodies, and farmer cooperatives have collaborated to create scalable residue management systems. These pilot efforts, if replicated and refined, offer a blueprint for national roll-out.

In conclusion, addressing crop residue burning through advanced machinery in India is not a question of "if" but "how." Technology is already available and functional; now, the challenge is to make it viable, inclusive, and widely adopted. This calls for a concerted multi-stakeholder strategy that integrates technological innovation, policy reforms, farmer-centric education, and private sector investment. The research confirms that sustainable crop residue management can become both an environmental imperative and an economic opportunity—provided the focus shifts from machinery promotion to ecosystem development. India stands at the cusp of a green revolution in crop waste utilization, and timely, collaborative action can unlock its full potential.

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