Tackling Crop Residue Burning in India: Systems Insights, Policy Reforms, and Localized Solutions

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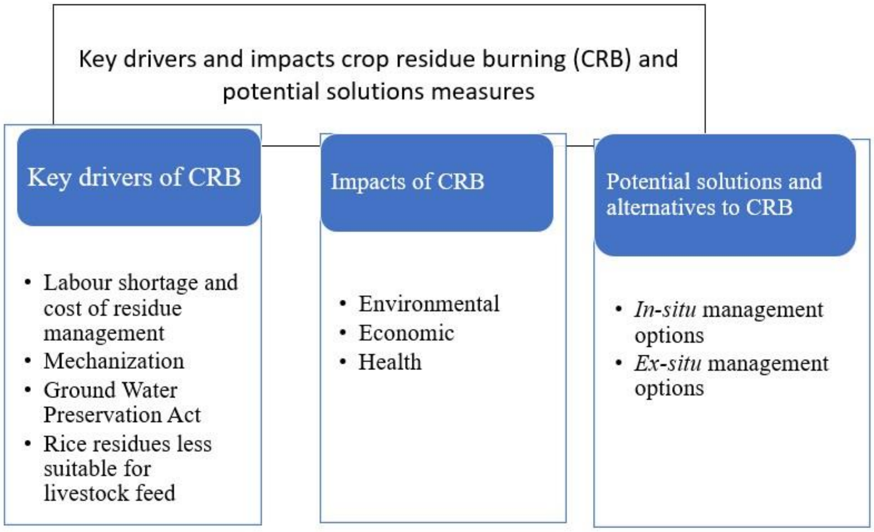

Contents

Abstract

Background: Crop residue burning (CRB) in India causes severe air pollution and greenhouse gas emissions, harming public health, degrading soil, and accelerating climate change. While technological and policy interventions for sustainable residue management exist, they often focus on short-term fixes and fail to address systemic drivers necessitating a systemic transition framework.

Methods: This study advances previous reviews by triangulating insights from a systematic literature review with empirical evidence gathered through Focus Group Discussions and Key Informant Interviews, offering a grounded understanding of the behavioral, institutional, and technological barriers to sustainable crop residue management. Building on these integrated findings, it proposes a novel, co-designed transition framework that addresses the systemic drivers of CRB and charts a pathway toward inclusive and scalable solutions.

Results: Our findings reveals that crop residue burning is driven not merely by technological barrier but by a deeper misalignment between policy design and ground realities, demanding system-wide reforms that integrate technological innovations, governance, incentives, and local agency. CRB in India is driven by cereal-dominant farming systems, widespread mechanization, labor shortages, narrow post-harvest planting windows, and the poor feed value of some residues. Although farmers are aware of its impacts and the available alternatives, barriers such as limited access to residue management machinery, economic constraints, and weak legal enforcement have led to low adoption of sustainable practices. We highlight the need for an integrated approach that includes not only technological innovations but also regulatory enforcement, policy reforms and financial incentives.

Conclusion: We propose an integrated transition framework that incorporates environmental justice, realigns incentives through targeted policy reforms, and empowers community-led decision-making offering a sustainable and inclusive pathway to address crop residue burning.

Key Words: Rice-Wheat Cropping Systems, Crop Residue Burning, Air Pollution, Sustainable Agriculture, Climate Change

1. Introduction

Crop residue burning (CRB) has emerged as one of the most persistent environmental and agricultural challenges in South Asia, particularly in the intensive rice-wheat cropping systems of the Indo-Gangetic Plains in North-Western India. India generates an estimated 683 million tons of crop residue annually from agricultural production (Kurinji and Kumar, 2021; Jain et al., 2018), a significant portion of which is burned. Crop residue burning (CRB, Figure 1) leads to air pollution and greenhouse gas (GHG) emissions resulting in significant social costs associated with transportation disruptions, school closures, human health risks, and climate change (1,2)

A multitude of factors contribute to crop residue burning (CRB) in India. These include policy incentives that favor rice–wheat cropping systems such as free electricity for irrigation and minimum support prices along with the widespread use of combine harvesters that leave substantial residue in the field. The problem is further compounded by narrow post-harvest sowing windows, driven by the adoption of long-duration rice varieties and irrigation-linked cropping mandates, as well as the economic unviability of residue collection and management for many farmers.

Recognizing these issues, the Indian government has supported technological interventions and introduced incentives as well as regulatory mechanisms to promote sustainable residue management and to curb CRB. For example, in 2018 the state of Punjab launched a subsidy program to cover upto 50% cost or USD 1800 per unit of Happy Seeder (Singh et al., 2020), a machine which can drill seed over heavy loads of loose and anchored crop residues (4). Another example is the *'Mera Pani-Meri Virasat'* scheme by the Haryana government, started in the Kharif season of 2020. Under this initiative, the government is providing financial assistance of Rs. 7,000 (USD 84) per acre to farmers for diversifying the paddy crop with alternative crops like maize, cotton, millet, pulses, vegetables, and fruits. Quantity-based interventions involve regulating the amount of residue burned through emissions standards, strict burning regulations, and penalties for non-compliance. In 2015, the National Green Tribunal (NGT) banned CRB in Rajasthan, Uttar Pradesh, Haryana and Punjab. This ban set quantity restrictions on burning and imposed fines on violating farmers (5). Alongside these direct regulatory actions, government has also taken indirect approaches like disseminating knowledge on alternatives to CRB, farmer training programs and extension services to raise farmers' awareness about the negative consequences of CRB. However, enforcement has been inconsistent, and adoption remains limited.

A substantial body of literature has examined CRB' impact and technological alternative solutions (Anand et al., 2021; Jethva et al., 2019; Ravindra, Singh, Mor, et al., 2019; Singh et al., 2022; Turmel et al., 2015). However, full understanding the factors driving CRB and their relative importance, successes and limitations of existing initiatives to curb CRB and challenges in transitioning away from burning is still lacking. Moreover, these reviews seldom integrated empirical insights from local actors. This paper fills that gap by integrating peer-reviewed knowledge with farmer and stakeholder interviews to produce a transition framework grounded in real-world complexity and the roles of different stakeholders in this transition.

2. Methodology

2.1. Literature review

To ensure a rigorous and comprehensive search, we followed a systematic review protocol based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. Our search strategy incorporated multiple databases, including Google Scholar, Scopus, and Web of Science. We used a combination of specific search terms, including primary terms such as 'crop residue,' 'crop waste,' 'harvest waste,' and 'leftover crop'; action-related terms like 'burning,' 'stubble burning,' and 'field fire'; technology-related terms such as 'combined harvester' and 'zero-tillage'; crop-specific terms including 'rice' and 'wheat'; and the geographic limiter 'India'. These terms were used individually or in combination with Boolean operators (AND, OR) to maximize the relevance and comprehensiveness of our search results.

Our initial search yielded 550 papers, which we then subjected to a screening process. We applied specific inclusion and exclusion criteria to ensure the relevance and quality of the selected studies. Included papers focused on crop residue burning practices in India, examined environmental and health implications of crop residue burning, investigated underlying drivers of the practice, or proposed potential remedies for reducing it. We excluded studies not conducted in or relevant to the Indian context, publications before 1990, and nonpeer-reviewed articles or grey literature. This systematic process resulted in 77 papers being considered relevant and retained for detailed synthesis. These papers form the core of our literature review and subsequent analysis.

2.2. Key Informant Interview and Focus Group Discussions

To complement our review, we collected primary data on the extent of crop residue burning, farmers' perception on the socio-economic and environmental impact of CRB together with motivation and challenges in adopting sustainable residue management solutions through Key Informant Interviews (KIIs) and Focus Group Discussions (FGDs). This mixed-method approach allowed us to gain deeper insights into the complex dynamics of CRB practices in the region.

We conducted two KIIs, interviewing local leaders, specifically village heads (Sarpanch) and local-level agricultural extension workers. These individuals were selected due to their pivotal roles in local governance, decision-making processes, and agricultural knowledge dissemination. As elected heads of the local self-government, the Sarpanch possess valuable insights into agricultural practices, traditional customs, and community dynamics. This purposive selection ensured that interviewees had both policy exposure and operational insight into community-level residue management. The KIIs covered three main areas: the historical context of agricultural practices in the region, policy information related to crop residue management, and community attitudes towards crop residue management and burning. We obtained informed consent from all participants before conducting the interviews, each of which lasted approximately 60-90 minutes.

FGDs were also conducted in two villages: Uncha Samana and Mehamadpur in the Karnal District of Haryana. These villages were purposively selected in consultation with local experts, as areas where the majority of farmers burn crop residues. A total of four FGDs were held, two in each village, with 12 to 18 participants per group. All participants, aged between 15 and 65, were directly engaged in agricultural activities. The discussions explored current residue management practices, motivations and barriers to adopting alternatives, perceived environmental and health impacts of CRB, awareness and opinions on existing policies and interventions, and suggestions for achieving more sustainable residue management..

The transcripts were analyzed using thematic analysis, involving the coding of emerging concepts and ideas, and organizing the data into narrative themes aligned with these codes. This process enabled the identification of key patterns related to the drivers of crop residue burning, perceived environmental and health impacts, stakeholder perspectives on policies, and potential solutions. Responses from Focus Group Discussions (FGDs) and Key Informant Interviews (KIIs) were triangulated to capture both converging and diverging viewpoints across different stakeholder groups.

3. Results and Discussions

3.1. India’s Regulatory and Incentive Mechanisms in Response to CRB

Figure 1 summarizes the evolution of Indian policy regimes that directly or indirectly influenced CRB practices. The Indian government has prioritized food security since independence and took steps to intervene in foodgrain markets to make staples affordable and accessible (11). Introduction of high-yielding varieties of rice and wheat coupled with wide-scale adoption of agro-chemicals and irrigation in 1960s significantly increased agricultural productivity leading to the Green Revolution. To support farmers in this endeavour, the government provided input subsidies and facilitated access to credit. In 1966-67, the Minimum Support Price (MSP) mechanism was instituted (12). MSP acts as a floor price, ensuring that farmers receive remunerative prices for designated crops, especially wheat and rice. The implementation of these policies and programs encouraged farmers to grow wheat and rice inadvertently creating intensive rice-wheat production systems. These policies, while aimed at increasing food security, unintentionally created monoculture incentives and tight cropping calendars, making CRB a default practice.

In response to the urgent need to address CRB, the Indian government has implemented regulatory measures and laws. The Air Prevention and Control of Pollution Act of 1981 empowered state governments to adopt measures prohibiting CRB to control air pollution. However, significant actions were not taken until 1998, when the Supreme Court assigned the Environment Pollution Prevention and Control Authority (EPCA) responsibility for addressing transboundary air pollution in Delhi. In 2015, the National Green Tribunal (NGT), an environmental court in India, imposed a ban on CRB in the states of Punjab, Haryana, Uttar Pradesh, and Rajasthan. The NGT directed North Indian state governments to impose penalties on non-compliant farmers, ranging from INR 2,500 to 15,000 (USD 30-180) based on landholding size (13). While the NGT ban represents a bold legal step towards curbing air pollution, especially in region surrounding the capital of Delhi, enforcement inconsistencies and sociopolitical backlash have weakened its real-world impact. FGD respondents in Karnal mentioned awareness of the ban but expressed low fear of penalty due to lack of enforcement.

To coordinate and streamline stakeholder efforts to mitigate air pollution including CRB in National Capital Regions, the Government of India introduced the ‘Commission for Air Quality Management in National Capital Regions and Adjoining Areas Act’ in 2020. However, limited farmer representation in this Commission has drawn criticism from civil society groups and researchers.

The National Policy for Management of Crop Residue (NPMCR) was introduced in 2014-2015 to address CRB. However, the lack of actionable timelines or accountability mechanisms severely limited its operational impact, as observed in FGD responses from Haryana where no formal NPMCR awareness was reported. In 2017, the Ministry of Environment launched an awareness campaign on alternate residue management.

In addition to these regulatory measures, the Indian government has recognized the importance of providing financial incentives to farmers for sustainable management of crop residues and not burning them. One notable initiative is the Central Sector Scheme on 'Promotion of Agricultural Mechanization for *In-Situ* Management of Crop Residue,' launched in 2018.[1] This scheme aims to encourage the adoption of *in-situ* residue management practices by providing financial assistance for the purchase of machinery and equipment. Farmers can avail subsidies ranging from 50% to 80% of the capital cost, depending on the type of equipment and the category of beneficiaries. Under these schemes, farmers received subsidies to purchase crop residue management machineries such as Super Straw Management System (SMS) for Combine Harvesters, Happy Seeders, Hydraulically Reversible MB Plough, Paddy Straw Chopper/Shredder, Mulcher,

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[1] https://pib.gov.in/Pressreleaseshare.aspx?PRID=1707021

Shrub Master, Rotary Slasher, Zero Till Seed Drill, Super Seeder, Crop Reaper/Reaper Binder, Straw Baler and Rakes. However, the responses from KII and FGD in Haryana reveal that machinery subsidies often fail to reach marginal farmers who lack capital even for co-financing.

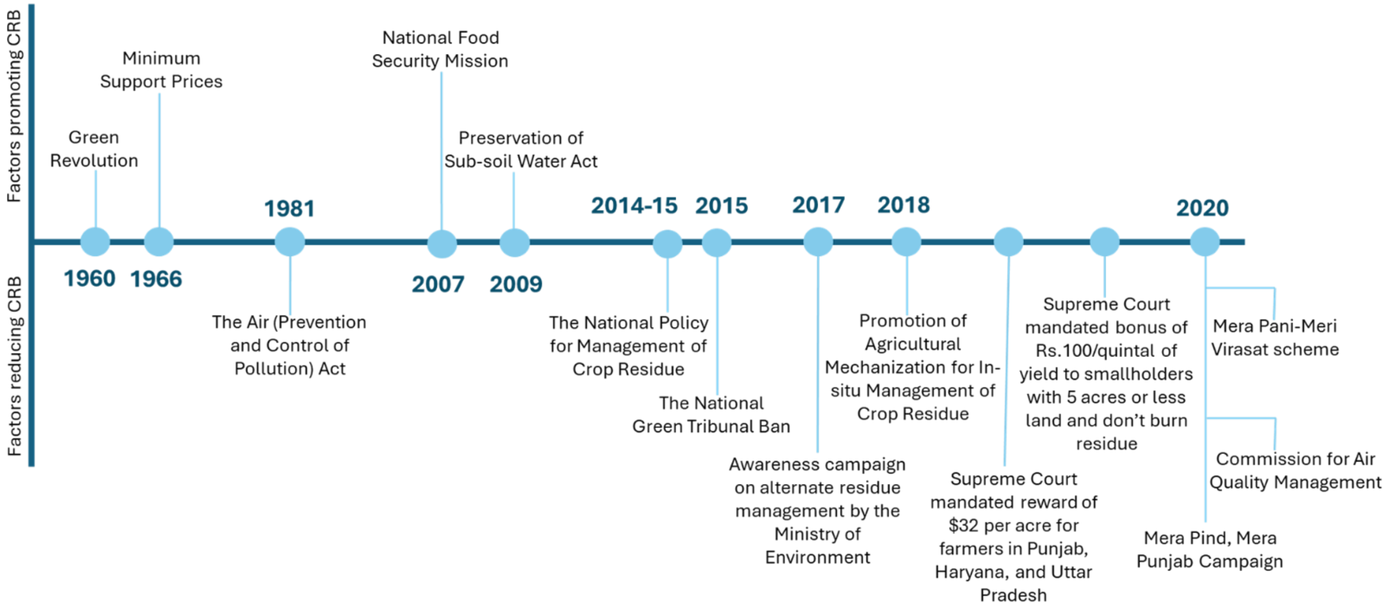
A technological advancement that has played a crucial role in reducing CRB is the adoption of balers. These machines collect and compress crop residues into bales, making storage, transport, and subsequent use more manageable and efficient. This technology has gained prominence in recent years, with the government promoting the establishment of Custom Hiring Centres (CHCs) equipped with these machines. The CHCs serve as centralized facilities that rent these machines out to farmers, enabling them to effectively manage crop residues without resorting to burning. Despite their utility, FGDs revealed that balers remain underutilized due to maintenance issues and difficulty accessing CHCs during peak seasons. State government should evaluate CHC efficiency and target regions with low machine density.

The Indian government has encouraged the setting up of biomass-based power plants through policy measures and financial incentives, promoting the use of crop residues as feedstock for electricity generation. This approach reduces dependence on fossil fuels while mitigating the environmental impact of open-field burning. The integration of crop residues into energy production has not only helped curb burning practices but has also created additional income opportunities for farmers. However, the viability of such plants depends on a consistent, economically transported residue supply, which was a concern echoed by local stakeholders during KII and FGD. Policy should emphasize feedstock aggregation hubs in different locations to ensure logistical feasibility.

In 2019, through a reward system mandated by the Indian Supreme Court, farmers in Punjab, Haryana, and Uttar Pradesh were instructed to receive a monetary incentive of USD 32 per acre for refraining from burning their crop residues. Additionally, small-scale farmers with up to 5 acres of land were entitled to a bonus of INR 1,000 (about USD 12) per ton of yield, amounting to around INR 3,000 (USD 36) per acre. Given the average yield in Punjab of 3 tons per acre, small farmers were entitled to receive 3,000 Indian Rupees per acre (ca USD 36), slightly higher than the recommendation of 2,500 Rupees per acre (ca USD 30) proposed by Jack et al. (2022) based on a randomized control trial. To enforce compliance, penalties ranging from USD 35 to

USD 210 were authorized, with the National Remote Sensing Agency (NRSA) empowered to identify violations through satellite or on-site monitoring. However, focus group discussions revealed that while the incentives were appreciated, delays in payment and weak enforcement of penalties significantly undermined their effectiveness.

The *'Mera Pind, Mera Punjab'* (my village, my Punjab) campaign, launched in 2020 by the Punjab government, aimed to encourage farmers to manage crop residue in an environmentally friendly manner by offering monetary rewards at the village level. Villages that achieved 100% compliance with the CRB ban were eligible to receive cash prizes ranging from 1-5 million Rupees (USD 12000-60000), based on village size. The prize money was intended for community development projects, such as infrastructure improvements, sanitation enhancements, or the establishment of parks and sports facilities.



Regulatory and incentive mechanisms that promoted or reduced CRB in India

3.2. Drivers of CRB in India

A multitude of factors are responsible for CRB in intensive rice-wheat production areas of India. These factors are systemic, interconnected, and shaped by both technological adoption patterns and macroeconomic policy design.

Labour shortage and cost of residue management

The prevalence of labour shortages in agricultural regions is a crucial factor contributing to CRB. Farmers frequently face difficulties finding adequate workforces for manual residue management due to labour out-migration for industrial job, making burning an attractive and seemingly efficient option. During FGD, farmers reported that seasonal migration of workers often leaves them with insufficient labour to handle residues in a timely manner. This issue is compounded by rural migration and government employment guarantee programs like the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA). While MGNREGA has helped reduce rural vulnerability by providing secure local employment, its timing and structure have inadvertently conflicted with peak agricultural labor demand. Bhattacharyya et al. (2021) identified such programs as factors needing to be addressed to mitigate persistent CRB. The costs of residue collection, transportation and utilization, which have risen as production volumes increased (16) also encourage farmers to opt residue burning. Burning residues requires less labour and also eases seedbed preparation with less fuel consumption (17,18) appearing as cost-effective option for farmers.

Mechanization

Mechanization, while increasing efficiency, unintentionally escalated CRB. Use of combine harvester has become the preferred harvesting method for paddy due to its cost-effectiveness and time efficiency. Currently 85-90% of rice and wheat in Haryana and Punjab are harvested using combine harvester (19) and the number of self-propelled combine harvesters in Punjab alone reached nearly 8,000 units during 2018-19 (20). Increased adoption of combined harvester escalated the difficulty in residue management as crop residues are unevenly spread across fields and left behind, making their recovery difficult (18,21). At the same time, combine harvesters leave significantly taller anchored residues, approximately 1-2 feet in height, compared to manual harvesting in which case farmers cut closer to the crop base, leaving less than 6 inches of residue (22,23). Additionally, combine harvesters separate grains from the ear-head, leaving chaff and thus increasing the amount of residue left in the field compared to manual harvesting in which more straw tends to be removed (4). These loose residues generated during combine harvesting can interfere with subsequent crop tillage and sowing with traditional planter. Liu et al. (2019, 2020) reported that combine harvester adoption has driven observed CRB increases. Using satellite data and ground monitoring, they documented a significant rise of up to 142% in active fires and burned areas across the Western Indo-Gangetic Plain from 2003-2016. These findings align with several other studies that detected increased CRB activity through remote sensing data (Badarinath et al., 2009; Jethva et al., 2018; Kaskaoutis, Kumar, et. al., 2014; Liu et al., 2018). Crop residue burning has also increased with the increased use of rotavators for preparatory tillage, which functions best in clean field without crop debris (1).

Ground Water Preservation Act

This act, while successful in water conservation, introduced unintended agronomic pressures leading to CRB. This legislation aimed to conserve groundwater by delaying rice planting to coincide with monsoon rains, initially prohibiting transplanting before June 10, later adjusted to June 20. Delayed paddy transplantation compresses the interval between rice harvest and wheat sowing to approximately two weeks (Singh et al., 2019). This, combined with the adoption of high-yielding, long-duration rice varieties, has further shortened the interval between rice harvest and wheat planting. This narrow timeframe exacerbates the challenge of removing residues left by mechanized harvesting, leading to the adoption of burning as the quickest option to get the field ready for the next crop. Studies by Chakravartty and Nasim (2015) and Gupta (2019) showed that the act successfully addressed groundwater depletion in Punjab and Haryana by regulating paddy transplantation. However, Singh et al., (2019), and Liu et al., (2018) revealed that the shortened window between rice harvest and wheat sowing due to this policy exacerbated CRB by leaving insufficient time for residue management. This tradeoff exemplifies the challenges of single-issue policy instruments in complex systems such as CRB and underscores the importance of evaluating cross-sectoral spillovers when designing environmental regulations.

Limited Feed Value of Rice Straw

A lesser explored cause of residue burning is the limited suitability of paddy straw as livestock feed in north-western states due to its high silica content, leading to low demand as feed (31). Singh et al. (1996) highlight that the high silica and lignocellulose content of paddy straw, along with low mineral and protein levels, restricts its nutritional value for livestock. Moreover, the high silica content can contribute to livestock diseases such as Degnala (Doberman and Fairhurst, 2000). Migo (2019) indicated that rice straw also contains elevated levels of oxalate, large quantities of which can be harmful to livestock. Moreover, the structural characteristics of rice straw and its high silica content make it challenging to chop and prepare as feed and results in poor palatability. However, developing improved processing methods or feed supplements could enhance its nutritional quality and palatability, thereby promoting its use as livestock feed and potentially reducing the need for CRB. Pilot programs at local level testing treated and fortified paddy straw may increase adoption.

Straw storage and use

Straw's low density and moisture retention make it difficult to store safely and economically, particularly in smallholder settings. Adequate land and facilities are necessary to accommodate straw bale storage. Where protected facilitates are not possible, bales stored on fields or field margins must be protected against adverse weather including windstorm. Storage is further challenged by rodent infestation and mould growth, particularly during the monsoon season and humid winter season of South Asia (4,33,34). During FGD, farmers also expressed concern about fire risk and pest infestations in stored straw, discouraging non-burning options. The lack of reliable markets and low returns from selling residues also perpetuate burning (Kaur, 2017; Haider, 2012). Prevention of fly ash use for brick manufacturing by the Ministry of Environment, Forest, and Climate Change in 2019 further reduced the use of rice straw (15).

3.3. Economic, environmental, and health impacts of CRB in India

Environmental Consequences

The negative environmental consequences of CRB are well-documented in India (Awasthi et al., 2011; Cusworth et al., 2018; Jain et al., 2016; Vadrevu et al., 2011). For example, Jain et al., 2016 estimated approximately 8.57 million tonnes of carbon monoxide, 141.15 million tonnes of carbon dioxide, and other major air pollutants were released due crop residue burning in 2008-2009. Studies by Liu et al., (2018), Cusworth et al., (2018), and Vadrevu et al., (2011) have highlighted the significant degradation of air quality and increased outdoor pollution levels in northern India due to agricultural fires.

During rice and wheat residue burning periods, levels of particulate matter-such as PM10 and PM2.5- in Delhi rise by up to 78% and 43%, respectively (38). Similar increase was also reported from Punjab and Haryana (Singh 2015). Air pollutants from CRB can also damage plant tissues, increase heavy metal assimilation, and facilitate pest growth. The release of volatile organic compounds and nitrogen oxides from CRB contributes to ground-level ozone formation, which harms crop metabolism (Augustaitis et al., 2010; Ghosh et al., 2019).

Beyond atmospheric consequences, CRB significantly undermines soil health, long-term fertility, and carbon sequestration potential. Crop residues contain essential nutrients like carbon, nitrogen, phosphorus, potassium, sulfur and micronutrients vital for plant growth, which are lost during burning (Singh et al., 2020) degrading soil quality and fertility (Turmel et al. 2015; Jat et al., 2016; Mandal et al., 2004). For example, burning rice residues results into complete loss of carbon, reducing carbon sequestration, along with losses of 90% of nitrogen, 60% of sulphur, and 20-25% of phosphorus and potassium (Singh et al., 2020). Increased soil temperature due to burning reduces microbial populations resulting into reduced nitrogen and carbon content in soil (Gupta et al., 2004), crucial nutrients for overall soil health.

Economic Consequences

The macroeconomic and localized economic burdens of CRB have increasingly quantified and deeply concerning . Recently, Lan et al. (2022) estimated the annual cost of premature mortality from CRB at USD

23 billion—equivalent to 38% of health expenditure. One notable impact is the decline in tourist visit, particularly in Delhi due to pollution in recent years (42). Ghosh et al. (2019) estimated that CRB-induced air pollution has costed 4.5-7.7% of India's GDP in 2018, which is projected to increase up to 15% by 2060 due to cumulative effects. Bimbraw (2019) reported yield and nutrient loss due to CRB in India to be approximately Rs 5 billion (USD 60 million) per year. In addition, air pollution reduces human productivity across sectors through pollution-related health issues and impaired visibility (44). Transportation disruptions and accidents related to poor visibility associated with CRB incur further costs. A study by Kumar et al., (2021) found a 10 μg/m^3 increase in PM2.5 as a result of CRB increased road accidents by 6.7% during the crop residue burning season. During KII and FGDs, village heads and farmers also attested that the smoke generated by burning is a major cause of highways accidents during residue burning seasons.

Human Health Consequences

Extensive research has established a strong correlation between burning-induced air pollution and a wide range of health issues, particularly among vulnerable populations such as children, elderly, and individuals with pre-existing conditions. These harmful effects include skin and eye irritation, severe neurological, cardiovascular, and respiratory diseases. Exposure to high levels of air pollution, including stubble smoke, have been linked to lung diseases (Saggu et al., 2018), eye and lung irritation (Kumar et al., 2015) reduced lung function, and higher risk of asthma and chronic pulmonary conditions (Ghosh et al., 2019). Chakrabarti et al., (2019) found that risk of acute respiratory infection increases threefold in areas with CRB prevalence.

An epidemiological study of 150 children across India found that the short-term rise in airborne particulate matter from CRB significantly deteriorated children's health triggering cognitive impairments and increased neurological complexity (Gupta, 2019). This aligns with the findings from Awasthi et al., (2010) who show that CRB has a negative impact on the pulmonary function of children's in Northwest India. Increased hospital visits due to CRB induced health issues (48) and total annual welfare loss due to health damages from CRB has costed approximately Rs 76 million (USD 100,000) per year in northern India (Kumar et al., 2015). More recent estimates by Lan et al. (2022) show that the annual cost of residue burning-induced premature mortality between 2003-2019 was approximately USD 23 billion. Pullabhotla & Souza (2022) show that exposure to agricultural fires in India raises hypertension risk by around 1.8% and leads to 14% of hypertension mortality, resulting in USD 9 billion in annual costs. Pullabhotla et al., (2023) show that CRB contributes to approximately 130,000 additional global infant deaths per year.

3.4. Potential solutions and alternatives to CRB

In this section, we discuss various *in-situ* and *ex-situ* options available for crop residue management to move away from CRB.

In-situ management options

The incorporation or surface retention of crop residue preserves valuable nutrients, improves soil fertility and quality, reduces erosion, and supports the growth of beneficial soil microorganisms. For example, rice straw typically contains an average of 0.61% nitrogen, 0.18% phosphorus, and 1.38% potassium, while wheat stubble have even higher nutritional value (Ravindra et al., 2019a) which will be added to soil if integrated or retained on the soil surface.

A range of agronomic, mechanical, and biological options are available to manage crop residues in the field without burning. For example, adoption of conservation agriculture techniques, including the use of machinery such as zero-tillage drills and Happy Seeders, provides effective solutions for managing crop residues without resorting to burning (Singh et al., 2008; Sidhu et al. 2015; Jat et al. 2020; Kumar et al. 2023). Planting crops over previous crop residues left on the soil surface, using zero-tillage or permanent beds, has been shown to increase soil organic carbon, enhance soil quality, and reduce environmental impacts (53).

Where zero-tillage or conservation agriculture cannot be practiced, straw incorporation using mechanized tools offers an effective alternative, enhancing soil fertility and increasing carbon sequestration. Integrating crop residues into the soil has been shown to improve soil fertility, elevate nutrient levels, increase organic matter content, and significantly boost crop productivity, particularly in wheat (Singh et al., 1996; Li et al., 2016; Ravindra et al., 2019a). These benefits can be further amplified by mixing crop residues with inorganic fertilizer, which significantly improves soil nutrient content (54). The Indian Agricultural Research Institute

(IARI) developed a crop residue bio-decomposer capsule to promote sustainable straw decomposition (Singh et al., 2022) in the field. However, farmers perceive its effectiveness is highly dependent on specific soil and weather conditions, giving mixed results.

However, for farmers to cease residue burning, alternative solutions must be feasible, affordable, accessible, and tailored to their specific production conditions. Discussions with village heads and farmers indicate that, although they recognize the negative externalities of crop residue burning, adoption of alternatives remains low due to limited awareness, rental constraints, and perceived uncertainties regarding the effectiveness of these solutions.

Ex-situ management options

In addition to on-site management, there are various *ex-situ* alternatives to CRB, which offer scalable, commercial opportunities for circular bioeconomy models. Composting is a highly effective solution, which involves decomposition of crop residue, resulting in the production of nutrient-rich compost that contains essential elements such as nitrogen (2%), phosphorus (1.5%), and potassium (1.4-1.6%) (55). The use of nutrient-rich compost derived from agricultural stubble has been shown to improve soil productivity and boost crop yields by approximately 4–9% (Sood, 2013).

Vermicomposting, another popular method, employs earthworms to biologically break down and stabilize organic materials present in crop residue. This process yields finely divided compost with high porosity, good water-holding capacity, and easily assimilable nutrients for plants (56). Wheat, millet, sugarcane, and pulse stubble have been found to produce valuable vermicompost when mixed with cow dung (Ravindra et. al., 2019b; Suthar, 2008). Another technique is mechanized windrow composting, which involves the use of a windrow turner to mechanically aerate the compost pile. This method enhances airflow, accelerating the composting process and resulting in nutrient-rich compost that is particularly beneficial for vegetable cultivation (56).

Pyrolysis, a thermo-chemical conversion of residues involving high temperatures and limited oxygen producing biochar - a porous, carbon-rich substance that improves soil quality and enhances carbon sequestration (57,59)- could be a viable alternative for managing agricultural residue. Application of biochar in the soil enhances soil carbon, water retention, and nutrient availability, improving plant growth and yields. Additionally, biochar's long-term carbon sequestration in soil contributes to climate mitigation.

Agricultural stubble holds potential for biofuel production, particularly in the form of bioethanol derived from lignocellulosic materials. Lignocellulosic biomass has gained attention as a favourable feedstock for biofuel production due to its lower carbon footprint compared to fossil fuels (60). Furthermore, crop stubble can also be utilized for biogas production through anaerobic digestion, leading to the generation of bio-methane. The biogas produced can be utilized as fuel for domestic heating, thereby reducing emissions resulting from indoor biomass burning.

Utilizing crop stubble as animal feed presents a promising option, especially for wheat stubble, which has higher nutritional value. Integrated crop-livestock production where livestock are fed on crop residue enhances circularity and sustainability of the production system.

Crop stubble can be used for combustion, gasification, or methanation to produce electricity and heat. It can be directly burned or co-fired with other biomass, and the resulting by-products like bottom ash and fly ash can be utilized in cement and brick manufacturing or for road construction. In India, the Ministry of New and Renewable Energy has supported the establishment of around 500 biomass-based power plants, many of which rely significantly on agricultural stubble. However, the use of fly ash in brick kilns has concerns over air pollution and the leaching of heavy metals, highlighting the need for proper management and environmental safeguards when repurposing this as residue management option.

Finally, crop stubble also has potential applications in various industries. It can be used as a raw material for alcohol refineries, bedding material for mushroom farming, fuel for boilers through gasification. Additionally, it can be utilized in the production of bio-lubricants, nano-silica, and manufacturing of pulp and paper. In the construction sector, agricultural stubble can be incorporated to produce different types of concrete and bricks, enhancing their strength and thermal properties. These alternative uses provide valuable opportunities to maximize the utilization of crop stubble and reduce waste while promoting sustainability and economic viability.

High-tech options like pyrolysis and biogas offer additional climate mitigation benefits but require infrastructural support from the government. FGD with farmers revealed limited knowledge and access to these solutions, suggesting the need for farmer-led demonstration programs to promote these solutions.

3.5. Framework for Sustainable Crop Residue Management to Reduce Burning

India’s ongoing challenge with CRB stems from a complex interplay of technological, policy, economic, and behavioral factors. It is not simply a byproduct of individual farmer choice but the consequence of interlocking structures: skewed incentives, time-pressured cropping cycles, weak institutional coordination, and under-valued ecosystem services. While existing interventions such as bans, subsidies, and technology promotion primarily address the symptoms, they often overlook the deeper structural drivers. Tackling this issue requires a shift from fragmented interventions to a systems-based transition framework that targets leverage points across the agri-environmental system. Baed on synthesis of literature, policy analysis and farmers insight, this section introduces a framework that integrates principles of environmental justice, policy reform, and decentralized decision-making highlighting the role of various stakeholders (Table 1) to foster sustainable and inclusive solutions to reduce CRB.

Internalizing Environmental and Social Costs: Farmers perceive CRB as economically rational option despite their significant health, environmental, and social costs on communities. Farmers expressed willingness to adopt non-burning options if clear economic offsets were available. Introducing the environmental cost such as carbon pricing or pollution cost-sharing at the regional or district level, establishing performance-based incentives for community-level emission reductions and promoting outcome-based incentives through public-private partnerships can reduce CRB at local level.

Reforming Agricultural Subsidies and Planning: India's current agricultural policies such as free electricity and minimum support prices promote rice wheat systems with tight cropping cycle that inadvertently contributes to CRB. To address this, strategies should focus on reorienting subsidies to encourage crop diversification, promote circular and regenerative practices, and align MSP and procurement with sustainability indices or decarbonization goals. For example, introduction of Green MSP scheme linking price supports to verified CRB reduction commitments could offer a scale model for aligning economic incentives with environmental outcomes.

Building Inclusive, Accountable Agricultural Governance: Current top-down approaches often neglect the realities on the ground, leading to limited adoption and community disengagement. Effective ownership from all relevant stakeholders requires the establishment of dedicated local-level institutions at sub-district level responsible for managing residue, monitoring compliance, and distributing government incentives. Such localized governance structures are essential to enhance trust, accountability, and active participation. Focus group discussions emphasized that, in the absence of these locally rooted bodies, enforcement efforts are often viewed as punitive and are more likely to be resisted or circumvented.

Table 1. Role of Government, Private Sector, Farmers, and Farmers' Organization for Sustainable Crop Residue Management to Reduce Burning

Stakeholder	**Key Issues**	**Roles and Responsibilities**
Government	• Weak, politicized enforcement • Misaligned subsidies favoring rice-wheat systems • Inadequate infrastructure and machineries • Limited service provision of residue management machineries	• Strengthen enforcement via depoliticized, empowered local agencies • Reform subsidies to support diversification • Expand smallholder access via direct support, loans, hiring centers • Invest in infrastructure for residue storage, transport, and use

	• Late rice planting regulation narrowing wheat planting window	• Launch 'Green MSP' linking support to CRB reduction
Private Sector	• High cost of machinery • Weak public-private coordination • Lack of scalable financing for residue use	• Develop affordable, smallholder-friendly machinery • Offer green bonds and CSR-backed credit for adoption • Promote CRB-free sourcing incentives • Scale agri-tech platforms for residue tracking and guidance • Collaborate on farmer training and robust M&E systems
Farmers & Farmer Organizations	• Low awareness of sustainable options • Financial constraints for smallholders • Limited participation in government policies on CRB Fragmented policy voice • Limited access to extension systems	• Test and adopt sustainable residue management practices • Raise awareness through local health and economic campaigns • Enable joint machinery use via cooperatives and producers' group • Advocate for inclusive policies and fair incentives

4. Conclusion and Recommendations

This paper offers an integrated understanding of CRB in India by synthesizing literature, policy review and farmer-level insight from KII and FGD and identifies leverage points for transformative change. Drawing on a synthesis of literature, policy analysis, and farmer-level insights, we propose a framework for sustainable and inclusive approach to reduce crop residue burning. This framework integrates principles of environmental justice, policy reform, and decentralized decision-making, while emphasizing the critical roles of diverse stakeholders in driving systemic change.

Findings suggest that CRB is complex issue driven by structural challenges such as technological access, behavioral inertia, fragmented governance, and poorly aligned subsidies. Addressing these barriers requires context-specific R&D, particularly for developing cost-effective, smallholder-friendly machinery and improving existing technologies. *In-situ* as well as *ex-situ* options exist for sustainable management of crop residues and to address burning issue. However, their adoption remains low due to high costs, limited availability, and doubts about effectiveness. Participatory testing and demonstrations, awareness campaigns, financial incentives, and targeted subsidies are essential to improve uptake of those sustainable options.

Sustainable crop residue management must be embedded in a broader transformation of India's agri-environmental policy. The approach should recognize the social costs of burning, realign subsidies, and empower farmers through participatory governance and green innovation pathways. Policy reforms should critically revisit and revise counterproductive incentives-such as free electricity, irrigation-linked rice planting calendar, and minimum support prices-that inadvertently encourage crop residue burning. Support should be redirected toward crop diversification, adoption of green technologies, and implementation of payment for ecosystem services. Additionally, leveraging opportunities in carbon credit markets can create further incentives for sustainable residue management.

The private sector can play a pivotal role in reducing CRB by increased manufacturing and promoting affordable, innovative machinery through targeted loans, subsidies, and public-private partnerships. Agri-tech startups can advance digital and precision farming solutions, while sustainable financing models like green bonds can support long-term residue management. Agricultural companies should invest in R&D to develop user-friendly technologies and processing centers. Additionally, the private sector can strengthen farmer capacity through training and demonstrations in collaboration with extension services and NGOs.

Farmers and their organizations play a critical role in reducing residue burning by adopting alternative management practices, raising community awareness, and facilitating collective access to relevant machineries. Strengthening their participation in policy processes and extension services is essential to ensure inclusive incentives and long-term behavioral change.

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DISCLAIMER

This study was conducted in accordance with the ethical standards of International Maize and Wheat Improvement Center (CIMMYT).