BKAP837
[1-10]

REVIEW ARTICLE Bhartiya Krishi Anusandhan Patrika

Stubble Burning in Northern India: Factors, Technological Solutions and Management Strategies-A Comprehensive Review

M.D. Saifuddin[1], Tahir Hussain[1], S. Sidharth[1], Keesam Manasa[1]

10.18805/BKAP837

ABSTRACT

Stubble burning in Northern India has emerged as a critical environmental and health crisis, driven by agricultural practices from the Green Revolution. Factors such as labour shortages, increased mechanization with combine harvesters, limited time for crop preparation and low utilization of crop residues as animal feed contribute to this widespread practice. Annually, approximately 178 million tons of crop residues remain unutilized, causing soil degradation and severe air pollution, impacting both agricultural productivity and public health. This study reviewed the factors contributing to stubble burning by farmers and techno-economic feasibility of innovative stubble management technologies, including the happy seeder, super seeder and bio-decomposers, which show promise in alleviating the adverse impacts of burning. However, challenges such as financial constraints, lack of awareness and insufficient policy support hinder their adoption. This review identified key barriers to effective implementation and outlines strategies to overcome these challenges. By synthesizing existing research and empirical data, this study aims to provide actionable insights for policymakers and stakeholders, highlighting the need for integrated approaches to promote sustainable agricultural practices. Collaborative efforts and informed actions are crucial to facilitating the transition toward sustainable stubble management, yielding benefits for both farmers and the environment.

Key words: Factors, Management strategies, Stubble burning, Techno-economic feasibility.

Agriculture is a cornerstone of India's economy, contributing over 15% to the nation's gross domestic product (GDP) (Singh *et al.,* 2020). With a diverse range of crops cultivated across its varied climatic zones, India stands as one of the world's largest agricultural producers. However, this sector faces numerous challenges, including climate change, soil degradation and resource scarcity (Tankiwala *et al.,* 2022). Among these issues, stubble burning has emerged as a critical concern, particularly in Northern India, where it has become a widespread practice following the harvest of major crops such as rice and wheat (Dube, 2022). Due to various socio-economic, institutional, technological and commercial obstacles, farmers are often forced to burn crop residue, resulting in numerous ecological issues (Udakwar and Sarode, 2023).

In India, cereal crop residues account for about two-thirds of the total 683 million tons (MT) produced annually, with surplus generation from various crops shown in Fig 1 (Jain *et al.,* 2018). A significant portion of these residues is used as fodder and fuel for domestic and industrial purposes. However, there remains a surplus of 178 million tons that goes unutilized (MoA and FW, 2019). Of this surplus, 87 million tons are incinerated, with Punjab alone contributing 9 million tons of burned paddy residue. The contributions from other major states are illustrated in Fig 2 (Jain *et al.,* 2018). This practice is deeply rooted in the agricultural culture of Northern India, shaped by the Green Revolution of the 1960s. While this initiative successfully increased food production, it also led to a large amount of agricultural waste, with stubble burning emerging as the easiest and cheapest method for residue management (Dube, 2022).

Stubble burning has several short-term benefits, such as quick field clearing for the next season, but it causes long-term damage to soil health. The ash produced degrades soil fertility, reduces moisture retention and disrupts the nutrient cycle, ultimately impacting agricultural productivity. The environmental consequences are also severe, as burning releases harmful pollutants like particulate matter (PM2.5 and PM10), carbon monoxide and greenhouse gases, which deteriorate air quality and pose serious health risks, including respiratory diseases (Gupta *et al.,* 2004). Additionally, the practice contributes to climate change by exacerbating global warming, creating a feedback loop where worsening climate conditions push

[1]Division of Dairy Extension, ICAR- National Dairy Research Institute, Karnal-132 001, Haryana, India.

Corresponding Author: M.D. Saifuddin, Division of Dairy Extension, ICAR- National Dairy Research Institute, Karnal-132 001, Haryana, India. Email: saifuddinmd786@gmail.com

How to cite this article: Saifuddin, M.D., Hussain, T., Sidharth, S. and Manasa, K. (2025). Stubble Burning in Northern India: Factors, Technological Solutions and Management Strategies-A Comprehensive Review. Bhartiya Krishi Anusandhan Patrika.1-10. doi: 10.18805/BKAP837.

Submitted: 07-02-2025 **Accepted:** 13-03-2025 **Online:** 15-03-2025

farmers to continue burning. Addressing stubble burning requires a comprehensive approach that integrates technological interventions and considers socio-economic factors influencing farmers' decisions. Innovations such as mechanical straw management systems and bio-decomposers offer promising alternatives, but their adoption remains limited due to financial constraints and lack of awareness (Dube, 2022; Dutta *et al.,* 2022).

This review aims to provide a comprehensive analysis of stubble burning in Northern India by exploring the factors contributing to this practice, assessing the techno-economic feasibility and impact of alternative technologies for crop residue burning management and identifying the constraints and strategies necessary for effective implementation. By synthesizing existing research and empirical data, this study seeks to contribute valuable insights that can inform future policy decisions and promote sustainable agricultural practices. Addressing stubble burning is not only crucial for improving air quality and public health but also for ensuring the long-term viability of agriculture in Northern India. Through informed action and collaborative efforts, it is possible to foster a transition toward sustainable practices that benefit both farmers and the environment.

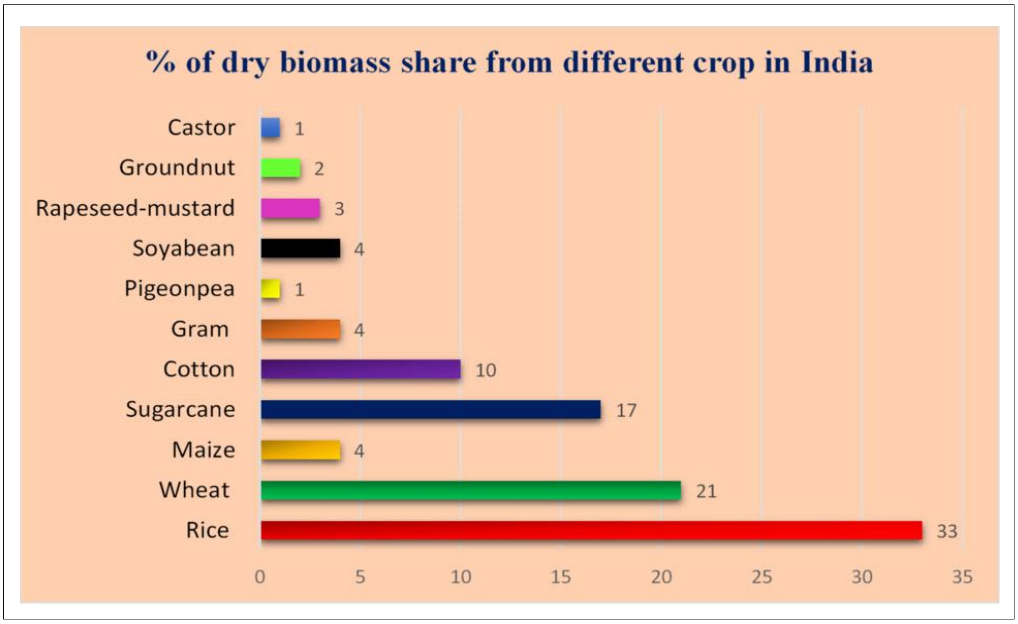

Fig 1: Percentage (%) of dry biomass share crop residue in India (Jain *et al.,* 2018).

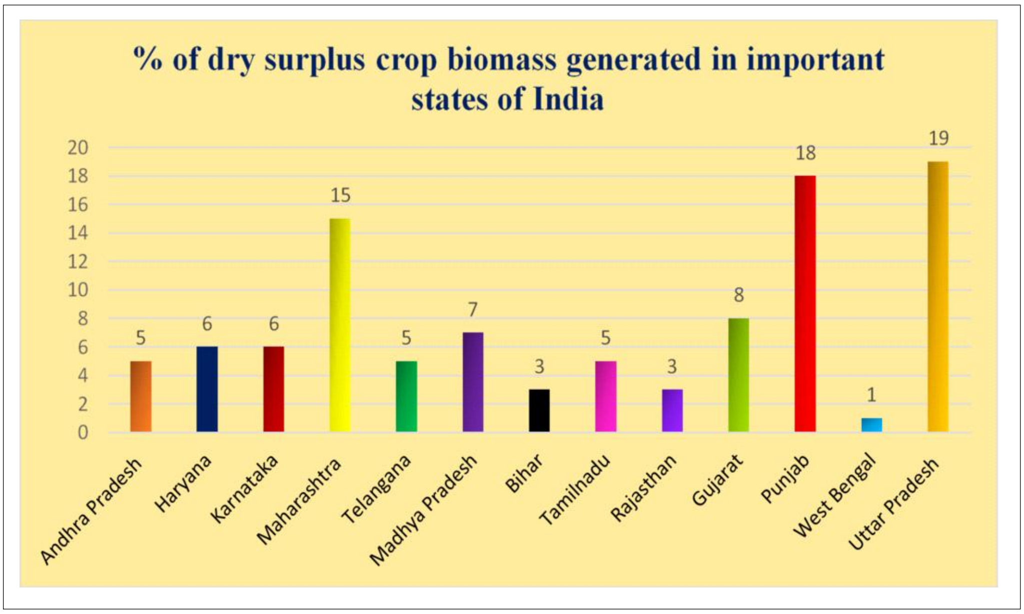

Fig 2: Percentage (%) of dry surplus biomass generated in important states of India (Jain *et al.,* 2018).

Factors contributing to stubble burning by farmers in northern india

Crop residue should not be considered waste; rather, it represents a valuable resource that is often converted into ash due to various interconnected factors. Key reasons for this practice include a shortage of labour during critical field operations, a limited time frame for preparing the land for subsequent crops, insufficient processing facilities and the widespread use of combine harvesters for paddy harvesting. In addition to these primary factors, several minor issues further exacerbate the situation. The following sections will discuss the significant reasons behind the prevalence of stubble burning.

Shortage of labour

In the current intensive agricultural system, sustaining farming operations with manual labor or animal power has become increasingly challenging. As a result, there has been a steady shift toward mechanization, with tractors and power tillers playing a dominant role in field operations (Lohan *et al.,* 2015; Singh *et al.,* 2013). Manual harvesting, though effective in removing most stubble for repurposing as livestock feed or thatching material, is still practiced in specific regions. For instance, basmati rice is often harvested manually to reduce grain breakage, as it is prone to lodging and preferred for fodder due to its lower silica content compared to hybrid varieties (Erenstein, 2011). However, in Haryana's Sirsa and Fatehabad districts, large landholdings and labour shortages have led to mechanical harvesting using combine harvesters, followed by stubble burning (MoA and FW, 2019). Punjab districts such as Sangrur, Bhatinda, Firozpur, Muktsar and Mansa have also witnessed significant stubble burning. Annually, about 11.3 million tons of crop residue is burned, with Haryana and Punjab contributing 16.9% and 49.47%, respectively (MoA and FW, 2019). Labor shortages are further exacerbated by employment guarantee schemes like MGNREGA, which provide secure rural employment, discouraging agricultural work. The National Sample Survey Office (NSSO) has also reported a declining trend in the agricultural workforce in recent years (Bhattacharyya *et al.,* 2021).

Farm mechanisation and adoption of combine harvester

Since the post-green revolution era, Punjab and Haryana have witnessed a significant rise in farm mechanization, coinciding with a growing labour shortage. This shift is primarily driven by the need to harvest hybrid rice cultivars before they lodge, as they are highly susceptible to shattering losses and the cost-effectiveness of mechanized operations. Traditional paddy harvesting requires approximately 150-200 man-hours per hectare, making it economically unviable for many farmers (Lohan *et al.,* 2015; Lohan *et al.,* 2018). As a result, combine harvesters have become the preferred solution. These fully automated machines integrate harvesting and threshing, significantly reducing labour dependency. However, they also pose a challenge for stubble management, as they leave behind 20-30 cm of crop residue, complicating land preparation for the next crop. In Punjab, the number of self-propelled combine harvesters surged to nearly 8,000 by the 2018-19 agricultural season (Grover *et al.,* 2017). This rise in mechanization has led to large quantities of residue up to 9 tons per hectare being left in fields (Mittal *et al.,* 2009). With limited alternatives, many farmers resort to burning stubble to clear their fields quickly for the next cropping season.

Narrow window for land preparation of subsequent crops

Farmers have a narrow window to sow wheat typically 7-10 days after harvesting basmati rice and 15-20 days after high-yielding rice varieties (Sahai *et al.,* 2011; Prem *et al.,* 2024). Previously, the long-duration rice varieties did not align well with the rice-wheat cropping system, compelling farmers to choose between growing either wheat or rice. However, advancements in temperature-insensitive, non-photoperiod sensitive varieties now enable the cultivation of both crops around 130-140 days for rice and 120-130 days for wheat. To achieve this, farmers must clear rice straw before wheat sowing in late November to early December (Kumar *et al.,* 2015), increasing reliance on stubble burning. While combine harvesters allow timely paddy harvesting, they also create major challenges. They leave behind 20-30 cm of stubble, which is difficult to remove and loose residues amounting to 7.5-9 tons per hectare, complicating collection and disposal (Jain *et al.,* 2014). With limited time and alternatives, many farmers resort to burning as the most practical solution for residue management.

Limited acceptance as animal feed

Paddy straw is rarely used as livestock feed in Northwestern India due to its high silica content (around 8% dry matter) and poor nutritional profile, including low minerals, protein and high lignocellulose (Singh *et al.,* 1996; Prasanthkumar and Kannan, 2018). While nutritionally similar to wheat straw, farmers prefer wheat straw for feeding. In some areas, rice straw is mixed with green fodder or used for grazing. Beyond its low nutritional value, several factors limit its acceptance: (1) the risk of 'Degnala' disease, (2) difficulties in chaff preparation and mixing, (3) low palatability due to small pubescence, requiring livestock adaptation and (4) high oxalate content (Singh *et al.,* 1996). These challenges contribute to its limited use as fodder.

Control of pests and weeds

Burning is often seen as an easy way to control pests, but it remains controversial. While it can temporarily reduce pathogen loads, it also harms beneficial soil microbes (Pathak *et al.,* 2011; Singh *et al.,* 2013). Many farmers hold the belief that burning can enhance soil productivity by decreasing both weed and pathogen populations (Lohan *et al.,* 2018). The resulting ash may briefly enhance phosphorus and potassium levels and neutralize soil pH. However, burning significantly depletes soil organic carbon (SOC), vital for soil health and fertility (Jat *et al.,* 2009).

Despite short-term benefits, its long-term impact on soil quality must be carefully weighed.

Storage challenges and commercial utilization

The bulky and fluffy nature of rice residue makes storage challenging, requiring substantial space (Sidhu *et al.,* 2015). According to Kadam *et al.,* (2000), Storing baled straw from 8,000 hectares demands nearly 80 hectares, about 1% of the cultivated area. Storage must be waterproof and wind-protected, as loose bales scatter easily. Rodent infestations further discourage storage, leading many farmers to burn the residue. Additionally, rice straw's hygroscopic nature, especially during monsoon, promotes mold and fungal growth, harming livestock health (Goswami *et al.,* 2020). Historically, brick kilns were among the largest consumers of rice straw; however, since 2019, the implementation of regulations by the Ministry of Environment, Forest and Climate Change (MoEFCC) regarding the use of fly ash in brick manufacturing has resulted in a substantial decline in straw consumption (Bhattacharyya *et al.,* 2021).

Reduced tractive force and energy savings

Burning paddy straw eliminates leftover material from the field, thereby simplifying the subsequent sowing process for tractors. This practice not only aids farmers in preparing an optimal seedbed for wheat but also contributes to fuel savings (Kaur and Rani, 2016; Lohan *et al.,* 2015). Singh *et al.* (2018) found that less than 1% of farmers engaged in conservation agriculture (CA) incorporate residue due to the higher costs associated with this method. Consequently, many farmers prefer burning straw to quickly clear the field for timely sowing operations.

Impact and techno-economic feasibility of stubble burning management technologies

Stubble burning is a prevalent agricultural practice that poses significant environmental and health risks, contributing to air pollution and greenhouse gas emissions. As the demand for sustainable farming intensifies, it becomes essential to explore alternative stubble management technologies that not only mitigate these impacts but also enhance agricultural productivity. This paper examined the impact of various stubble burning management technologies, focusing on their techno-economic feasibility, as mentioned in Table 1. By assessing both the ecological benefits and the economic viability of these alternatives, we aim to provide insights that can guide policymakers and farmers towards more sustainable agricultural practices.

Constraints in adoption of stubble burning management technologies

Perceived benefits and risks

Farmers' adoption of technologies like the Happy Seeder is influenced by perceived risks, such as increased rat populations and weed growth, which threaten wheat yields. Limited impact of extension services further hinders adoption. Providing multiple residue management options (e.g., balers, Happy Seeders) alongside stricter burning regulations can enhance uptake (Gupta, 2012). However, Kanokanjana and Garivait (2013) highlighted that farmers favour open burning due to perceived short-term benefits like pest control and soil texture improvement, despite its environmental harm. Addressing these perceptions through education and awareness is crucial for promoting sustainable residue management.

Economic barriers

Economic barriers hinder the adoption of sustainable technologies like the Turbo Happy Seeder Technique (THST). Despite subsidies, high initial costs and the need for manual labour for residue distribution discourage farmers (Singh *et al.,* 2021). With an operational window of just 25 days per year, THST use is restricted during key planting periods. Kaur (2017) highlighted additional challenges like limited residue buyers and weak state support, pushing farmers toward stubble burning. Enhancing financial aid, market incentives and policy interventions is crucial to promoting sustainable residue management and reducing reliance on burning.

Operational challenges

The adoption of stubble management technologies poses operational challenges, especially for small and marginal farmers. High costs of Turbo Happy Seeders and tractor rentals create financial barriers (Chaudhary *et al.,* 2019). Farmers also face pest infestations, nutrient deficiencies and poor seed germination due to heavy straw loads, impacting yields. Additionally, inefficient straw management leads to machinery failures and planting delays. These challenges discourage investment in new technologies. Enhancing financial support, improving machinery efficiency and strengthening extension services is essential to promote widespread adoption of sustainable residue management practices.

Custom hiring and accessibility barriers

Jambagi *et al.,* (2023) identified key barriers to Happy Seeder adoption, particularly in custom hiring. High rental costs and delayed subsidies create financial challenges, while limited availability during peak seasons restricts access. Resource allocation favours large farmers, leaving smallholders disadvantaged. Additionally, rental service viability is impacted by payment delays and machinery wear, discouraging providers. Unequal subsidy distribution between custom hiring centers and individual farmers further limits access. Addressing these issues through fair subsidy policies, timely payments and improved access to machinery is crucial to promoting wider adoption of Happy Seeders for sustainable residue management.

User perceptions of stubble management technologies like the PUSA decomposer revealed the significant barriers to adoption. Many farmers cited the

Table 1: Impact and techno-economic feasibility of technological interventions in stubble burning management.

Authors	Technological Intervention	Area of study	Impact and techno-economic feasibility of technology
Dhaliwal *et al.* (2011)	Happy seeder	Uttar Pradesh and Punjab	Increased land efficiency: Saves 5,912 ha^{-1} compared to conventional tillage. Increased net returns for Mung bean with Turbo Happy Seeder Technique (THST). Enhanced soil structure, minimized terminal heat stress and lowered pre-sowing irrigation requirements.
Gathala *et al.* (2011)	Turbo Happy Seeder Technique (THST)	Meerut, Uttar Pradesh	Zero tillage wheat-THST produced wheat grain yields that were 10% higher than conventional tillage wheat (CTW) and 9% higher than zero-tillage wheat without rice residue (ZTW). Enhanced soil physical properties, contributing to better wheat productivity. Effective management of canopy and soil surface temperatures, benefiting crop growth.
Yogi *et al.* (2015)	Turbo happy seeder technique	Haryana	Economic feasibility: The benefit-cost ratio is 2.21 for the Turbo Happy Seeder compared to 2.02 for zero tillage, indicating its economic viability.
Iqbal *et al.* (2017)	Happy seeder zero tillage (HSZT)	Gujranwala	Enhanced germination and yield: HSZT produced higher germination rates and greater yields compared to the Conventional Method (CM). Increased net income: HSZT achieved a net income of Rs. 112,938 per hectare, with a cost-benefit ratio (CBR) of 1:1.51, while CM. yielded a net income of Rs. 102,602 per hectare with a CBR of 1:1.33. Timely Sowing and Resilience: HSZT facilitates timely wheat sowing in a single pass and makes crops more resistant to rain and excessive irrigation. Singh *et al.* (2020) Turbo Happy Seeder Technique (THST) Karnal, Haryana. Resource Efficiency: Machine labour, seed costs and irrigation positively impacted wheat yields**.** Production Elasticity: An elasticity of 1.462 indicates increasing returns to scale, suggesting resources are under-utilized**.**
Keil *et al.* (2021)	Happy seeder	Punjab	Cost savings: The Happy Seeder can save 161 INR per quintal, translating to an average total savings of 8,775 INR per hectare**.**
Saini and Brar (2021)	Super seeder	Punjab	It is a tractor-operated implement that performs three key functions:· Ploughs the field to prepare it for the next crop· Mixes the crop residue from the previously harvested crop with the soil· Sows the seeds for the next crop simultaneously
Jambagi *et al.* (2023)	Happy seeder	Karnal, Haryana	Increased earnings: realized a yield boost of around 4 quintals per hectare, leading to an additional income of Rs. 8,223. Cost reductions: The happy seeder method resulted in a savings of Rs. 8,799 per hectare due to: • Savings of Rs. 2,062 from 32.7 hours of reduced labour

Table 1: Continue...

Table 1: Continue...

			• A reduction of 4.4 ploughings for land preparation, saving Rs. 5,520 • Decreased seed usage (12 kg), which saved Rs. 427 • Lower irrigation expenses amounting to Rs. 790 per hectare. Net benefit: In total, adopting the happy seeder yielded an approximate net benefit of Rs. 10,074 per hectare in wheat farming.
Jambagi *et al.* (2023)	Pusa decomposer	Karnal, Haryana	Low application cost: Approximately Rs. 20 per pouch (four capsules) is required for one hectare, effective for 10-12 tonnes of straw, in addition to labour costs for spraying. User satisfaction: About half of the users reported full satisfaction with the technology, with larger. farmers expressing higher levels of satisfaction than smaller farmers. Yield boost: PUSA decomposer users experienced an increase in yield of 0.30 quintals per hectare, highlighting potential economic and environmental benefits.
Zaidi (2021); Biswas and Das (2023)	Pusa decomposer	-	It offers an eco-friendly and cost-effective solution to address crop residue burning, with a single packet of Pusa bio-decomposer capsules priced at just INR 20.

need for extra irrigation and the 25-day waiting period for decomposition as key challenges, jeopardizing timely wheat sowing. Additionally, limited understanding and accessibility of the technology have contributed to poor or non-adoption. Many farmers reported feeling only partially satisfied with the technology, underscoring the importance of enhancing education and support to facilitate its broader acceptance. Addressing these multifaceted barriers is crucial for promoting sustainable agricultural practices and ensuring that farmers can effectively transition away from traditional methods of stubble burning.

Strategies for effective crop residue management

The widespread burning of rice residue poses a significant threat to both the environment and society. It is also irrational to waste this valuable resource, which has numerous industrial and domestic applications, from compost production to power generation. Baling is considered an effective method for managing rice straw; however, access to the necessary machinery is often limited. In the following section, the management strategies for rice residue are primarily categorized into two types: in-situ and ex-situ (Dutta *et al.,* 2022).

In-situ residue management

Rice residue is a valuable yet underutilized resource in agriculture. Modern rice cultivars have a harvest index of 0.4 to 0.5, meaning that for every ton of grain produced, nearly one ton of straw is generated. Residue management can be done through straw incorporation (allowing residue to decompose naturally in the field) or straw mulching (mixing residue into the soil during sowing) (Kumar *et al.,* 2015). Incorporating rice residue 10 to 20 days before planting enhances the growth and productivity of subsequent crops, such as wheat The benefits of retaining or incorporating rice residue in the field include.

One key advantage of rice residue retention is improved soil fertility, as decomposing residue releases nitrogen, phosphorus and potassium, enriching soil nutrient content and enhancing microbial activity(Gangwar *et al.,* 2006). The addition of organic matter increases cation exchange capacity, improving nutrient retention and availability (Chauhan *et al.,* 2012). Another significant benefit is moisture conservation, as retained residue acts as mulch, reducing evaporation and improving water retention. This is particularly beneficial in water-scarce regions, where it enhances crop resilience against drought and reduces irrigation needs (Lohan *et al.,* 2018). Rice residue also plays a role in weed suppression, as the mulch layer inhibits light penetration, reducing weed germination and minimizing reliance on herbicides (Kumar *et al.,* 2019). This helps crops grow with less competition for resources, improving yields. Soil erosion prevention is another advantage, as organic cover protects soil from wind and water erosion. By preventing topsoil loss, residue management contributes to long-term soil fertility and agricultural sustainability.

Additionally, rice residue incorporation improves soil structure, enhancing aggregation, aeration and drainage

(Dutta *et al.,* 2022). A well-structured soil supports deeper root penetration, allowing plants to access nutrients and moisture more efficiently, ultimately leading to better plant stability and higher crop yields.

Ex-situ residue management

Ex-situ management of crop residues involves handling and utilizing residues outside the field environment, focusing on their potential for various applications. This approach not only mitigates the issues associated with open burning but also promotes sustainable agricultural practices. Key strategies include.

Composting

Composting involves the collection of crop residues, which are then decomposed through aerobic microbial activity to produce compost. This process not only recycles essential nutrients back into the soil but also enhances soil fertility and structure. The organic matter in compost improves soil texture, increases moisture retention and promotes beneficial microbial activity (Jusoh *et al.,* 2013; Qiu *et al.,* 2012). Moreover, composting helps mitigate the release of greenhouse gases associated with open burning, making it an environmentally friendly alternative (IRRI, 2019).

Bioenergy production

The conversion of rice straw and other agricultural residues into bioenergy through methods such as gasification and anaerobic digestion represents a sustainable energy solution (Ngan *et al.,* 2020). Gasification transforms organic materials into syngas, which can be used to generate electricity or produce biofuels. Anaerobic digestion, on the other hand, converts organic matter into biogas, which can be utilized for heating or electricity generation (Hiloidhari *et al.,* 2014; Rao *et al.,* 2010). Both processes contribute to reducing dependence on fossil fuels, enhancing energy security and lowering greenhouse gas emissions.

Animal feed

Pre-treatment of rice straw enhances its nutritional profile, making it more suitable as livestock feed. Common methods include soaking, chemical treatment, or ensiling, which can improve digestibility and nutrient availability (Aquino *et al.,* 2020). When mixed with higher-quality feed components, treated rice straw can significantly boost livestock productivity, leading to improved meat and milk yields. This approach not only provides an effective means of utilizing agricultural waste but also supports livestock farmers in enhancing their production efficiency.

Mushroom cultivation

Rice straw serves as an excellent substrate for mushroom farming, providing a dual benefit of waste management and economic opportunity. By utilizing agricultural residues for mushroom cultivation, farmers can generate additional income while simultaneously reducing waste (Kumar *et al.,* 2015). The cultivation of mushrooms on rice straw also promotes sustainable practices, as it utilizes otherwise discarded material, thus contributing to rural employment and food security.

Industrial uses

Crop residues can be transformed into raw materials for various industries. For example, rice straw can be processed into pulp for paper production or converted into biodegradable packaging materials (Dutta *et al.,* 2022; Kumar and Singh, 2020). Such industrial applications not only help in waste management but also create value-added products that support a circular economy. Utilizing agricultural residues in this manner reduces the environmental footprint associated with traditional raw material extraction.

Straw baling and storage

Baling rice straw is a practical strategy for managing residue volume, facilitating easier transportation and storage. This method reduces the immediate availability of straw for burning on-site, thus mitigating air pollution. Baled straw can be utilized later for various applications, including animal bedding, composting, or as a raw material for bioenergy production (Kumar and Singh, 2020). By organizing straw in a manageable form, farmers can maximize its utility while minimizing waste.

Erosion control and soil improvement

The incorporation of crop residues into constructed wetlands or using them as soil amendments serves to enhance soil quality and prevent erosion. Residues provide organic matter that improves soil structure and increases water retention, thereby supporting plant growth. In non-agricultural settings, using residues for erosion control helps stabilize soil, reduces runoff and promotes biodiversity (Bhattacharyya *et al.,* 2021). This practice aligns with sustainable land management principles, contributing to ecosystem health.

CONCLUSION

Stubble burning in Northern India presents a complex challenge driven by various socio-economic factors, including labour shortages, lack of awareness and inadequate access to alternative technologies. The techno-economic feasibility of interventions such as Happy Seeders and PUSA decomposers reveals significant potential for improving agricultural sustainability, yet adoption remains hindered by economic barriers, operational challenges and perceived risks. Farmers' reluctance to embrace new practices often stems from concerns about crop yields and the immediate utility of traditional methods. Effective strategies for stubble burning management must prioritize education and support for farmers, ensuring they understand the long-term benefits of residue management. Additionally, the promotion of ex-situ solutions, such as composting and bioenergy production, can enhance resource utilization and generate additional income streams. Policymakers should also consider equitable subsidy structures and improved access to machinery, particularly for smallholders. By addressing these multifaceted constraints and fostering an environment conducive to innovation, stakeholders can significantly mitigate the environmental impacts of stubble burning, enhance soil health and contribute to the overall sustainability of agricultural practices in the region.

ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to National Dairy Research Institute, Karnal for granting access to the required databases and research materials.

Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Informed consent

No animals were involved in this study.

Conflict of interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

REFERENCES

Aquino, D., Del Barrio, A., Trach, N.X., Hai, N.T., Khang, D.N., Toan, N.T. and Van Hung, N. (2020). Rice straw-based fodder for ruminants. Sustainable Rice Straw Management. Springer. pp. 111-129.

Bhattacharyya, P., Bisen, J., Bhaduri, D., Priyadarsini, S., Munda, S., Chakraborti, M., Adak, T., Panneerselvam, P., Mukherjee, A.K., Swain, S.L. and Dash, P.K. (2021). Turn the wheel from waste to wealth: Economic and environmental gain of sustainable rice straw management practices over field burning in reference to India. Science of the Total Environment. 775: 1-17.

Biswas, S. and Das, R. (2023). Pusa bio-decomposer: A promising option to stop crop residue burning. Trends in Agriculture Science. 2: 272- 275.

Chaudhary, A., Chhokar, R.S., Yadav, D.B., Sindhu, V.K., Ram, H., Rawal, S., Khedwal, R.S., Sharma, R.K. and Gill, S.C. (2019). In-situ paddy straw management practices for higher resource use efficiency and crop productivity in Indo-gangetic Plains (IGP) of India. Journal of Cereal Research. 11: 172-198.

Chauhan, B.S., Mahajan, G., Sardana, V., Timsina, J., and and Jat, M.L. (2012). Productivity and sustainability of the rice-wheat cropping system in the Indo-gangetic Plains of the Indian subcontinent: Problems, opportunities, and and strategies. Advances in agronomy. 117: 315-369.

Dhaliwal, H.S., Singh, R.P. and Kaur, H. (2011). Financial assessment of Happy Seeder. Conservation Agriculture News Letter. 8: 4-5.

Dube, A. (2022). Socio-economic assessment of crop residue burning in Northern India. M.Sc. Thesis. ICAR- Indian Agricultural Research Institute,. New Delhi, India.

Dutta, A., Patra, A., Hazra, K.K., Nath, C.P., Kumar, N. and Rakshit, A. (2022). A state-of-the-art review in crop residue burning in India: Previous knowledge, present circumstances and future strategies. Environmental Challenges,. 8: 1-16.

Erenstein, O. (2011). Cropping systems and crop residue management in the Trans-gangetic plains: Issues and challenges for conservation agriculture from village surveys. Agricultural Systems. 104: 54-62.

Gangwar, K.S., Singh, K.K., Sharma, S.K. and Tomar, O.K. (2006). Alternative tillage and crop residue management in wheat after rice in sandy loam soils of Indo-gangetic plains. Soil and Tillage Research. 88: 242-252.

Gathala, M. K., Vivak, K., Virender, K., Saharawat, Y. S., Blackwell, J. and Ladha, J.K. (2011). Happy seeder technology: A solution for residue management for the sustainability and improved production of the rice-wheat system of the Indo-gangetic plains. In 5th World Congress of Conservation Agriculture Incorporating 3rd Farming Systems Design Conference. September. 2011. pp. 94-95.

Goswami, S.B., Mondal, R. and Mandi, S.K. (2020). Crop residue management options in rice-rice system: A review. Archives of Agronomy and Soil Science. 66: 1218-1234.

Grover, D.K., Singh, J.M., Kaur, A. and Kumar, S. (2017). Technical report. state agricultural profile-Punjab. Agro- Economic Research Centre, Department of Economics and Sociology. Punjab Agricultural University, Ludhiana.

Gupta, P.K., Sahai, S., Singh, N., Dixit, C.K., Singh, D.P., Sharma, C. and Garg, S.C. (2004). Residue burning in rice-wheat cropping system: Causes and implications. Current science. 87: 1713-1717.

Gupta, R. (2012). The happy seeder: An agricultural solution to air pollution in South Asia. Policy brief 61. South Asian Network for Development and Environmental Economics (SANDEE). Kathmandu, Nepal.

Hiloidhari, M., Das, D. and Baruah, D.C. (2014). Bioenergy potential from crop residue biomass in India. Renewable and Sustainable Energy Reviews. 32: 504-512.

Iqbal, M.F., Hussain, M., Faisal, N., Iqbal, J., Rehman, A.U., Ahmad, M. and Padyar, J.A. (2017). Happy seeder zero tillage equipment for sowing of wheat in standing rice stubbles. International Journal of Advanced Research in Biological Sciences. 4: 101-105.

IRRI (International Rice Research Institute). (2019). Final report of the BMZ-funded IRRI sustainable rice straw management project.

Jain, N., Pathak, H. and Bhatia, A. (2014). Sustainable management of crop residues in India. Current Advances in Agricultural Sciences. 6: 1-9.

Jain, N., Sehgal, V. K., Singh, S. and Kaushik, N. (2018). Estimation of surplus crop residue in India for biofuel production. Technical report. Technology Information, Forecasting and Assessment Council (TIFAC), New Delhi.

Jambagi, R., Singh, D.R., Singh, A., Venkatesh, P., Nain, M.S. and Panghal, P. (2023). Are happy seeder and pusa decomposer potential options for sustainable ways of paddy straw management. Indian Journal of Extension Education. 59: 132-137.

Jat, M.L., Gathala, M.K., Ladha, J.K., Saharawat, Y.S., Jat, A.S., Kumar, V. and Gupta, R. (2009). Evaluation of precision land levelling and double zero-till systems in the rice-wheat rotation: Water use, productivity, profitability and soil physical properties. Soil and Tillage Research. 105: 112-121.

Jusoh, M.L.C., Manaf, L.A. and Latiff, P.A. (2013). Composting of rice straw with effective microorganisms (EM) and its influence on compost quality. Iranian journal of environmental health science and engineering. 10: 1-9.

Kadam, K.L., Forrest, L.H. and Jacobson, W.A. (2000). Rice straw as a lignocellulosic resource: collection, processing, transportation and and environmental aspects. Biomass and Bioenergy. 18: 369-389.

Kaur, A. (2017). Crop residue in Punjab agriculture-status and constraints. Journal of Krishi Vigyan. 5: 22-26.

Kaur, A. and Rani, J. (2016). An approach to detect stubble burned areas in Punjab by digitally analyzing satellite images. Journal for Research. 2: 64-69.

Keil, A., Krishnapriya, P. P., Mitra, A., Jat, M.L., Sidhu, H.S., Krishna, V.V. and Shyamsundar, P. (2021). Changing agricultural stubble burning practices in the Indo-gangetic plains: Is the Happy Seeder a profitable alternative? International Journal of Agricultural Sustainability,. 19: 128-151.

Kumar, A., Kushwaha, K.K., Singh, S., Shivay, Y.S., Meena, M.C. and Nain, L. (2019). Effect of paddy straw burning on soil microbial dynamics in sandy loam soil of Indo-gangetic plains. Environmental Technology and Innovation. 16: 1-10.

Kumar, P. and Singh, R.K. (2020). Selection of sustainable solutions for crop residue burning: An environmental issue in north-western states of India. Environment, Development and Sustainability. 23: 3696-3730.

Kumar, P., Kumar, S. and Joshi, L. (2015). Socioeconomic and environmental implications of agricultural residue burning: A case study of Punjab, India, Springer. Nature. pp. 26-29.

Lohan, S.K., Dixit, J., Kumar, R., Pandey, Y., Khan, J., Ishaq, M., Modasir, S. and Kumar, D. (2015). Biogas: A boon for sustainable energy development in India× s cold climate. Renewable and Sustainable Energy Reviews. 43: 95-101.

Lohan, S.K., Jat, H.S., Yadav, A.K., Sindhu, H.S., Jat, M.L., Chaudhary, M., Peter, J.K. and Sharma, P.C. (2018). Burning issues of paddy residue management in north-west states of India. Burning issues of paddy residue management in north-west states of India. Renewable and Sustainable Energy Reviews. 81: 693-706.

Mittal, S.K., Singh, N., Agarwal, R., Awasthi, A. and Gupta, P.K. (2009). Ambient air quality during wheat and rice crop stubble burning episodes in Patiala. Atmospheric Environment. 43: 238-244.

MoA and FW. (2019). Report of the committee on review of the scheme “Promotion of agricultural mechanization for in-situ management of crop residue in states of Punjab, Haryana, Uttar Pradesh and NCT of Delhi”. Department of Agriculture, Cooperation and Farmers Welfare, Government of India.

Ngan, N.V.C., Chan, F.M.S., Nam, T.S., Van Thao, H., Maguyon-Detras, M., Hung, D.V and Van Hung, N. (2020). Anaerobic digestion of rice straw for biogas production. Sustainable Rice Straw Management. Springer,. pp. 65-92.

Pathak, H., Tewari, A.N., Sankhyan, S., Dubey, D.S., Mina, U., Singh, V.K. and Jain, N. (2011). Direct-seeded rice: Potential, performance and problems: A review. Current Advances in Agricultural Sciences. 3: 77-88.

Prasanthkumar, K and Kannan, S.V. (2018). Rice residue management for rice based cropping system in Cauvery delta zone-A review. Agricultural Reviews. 39: 241-245.

Prem, G., Kumar, N., Poddar, A., Mehta, A.R. and Kumar, R. (2024). Residue and irrigation management for optimizing productivity and profitability of wheat in Ambala (Haryana). Indian Journal of Agricultural Research. 58(2024): 1079-1086. doi: 10.18805/IJARe.A-6324.

Qiu, J., He, J., Liu, Q., Guo, Z., He, D., Wu, G. and Xu, Z. (2012). Effects of conditioners on sulfonamides degradation during the aerobic composting of animal manures. Procedia Environmental Sciences. 16: 17-24.

Rao, P.V., Baral, S.S., Dey, R. and Mutnuri, S. (2010). Biogas generation potential by anaerobic digestion for sustainable energy development in India. Renewable and Sustainable Energy Reviews. 14: 2086-2094.

Sahai, S., Sharma, C., Singh, S.K and Gupta, P.K. (2011). Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India. Nutrient Cycling in Agroecosystems. 89: 143–157.

Sidhu, H.S., Singh, M., Singh, Y., Blackwell, J., Lohan, S.K., Humphreys, E., Jat, M.L., Singh, V. and Singh, S. (2015). Development and evaluation of the turbo happy seeder for sowing wheat into heavy rice residues in NW India. Field Crops Research. 184: 201-212.

Singh, J., Singhal, N., Singhal, S., Sharma, M., Agarwal, S. and Arora, S. (2018). Environmental implications of rice and wheat stubble burning in north-western states of India. Advances in Health and Environment safety. Springer, Singapore. pp. 47-55.

Singh, R., Yadav, D. B., Ravisankar, N., Yadav, A. and Singh, H. (2020). Crop residue management in rice-wheat cropping system for resource conservation and environmental protection in north-western India. Environment, Development and Sustainability. 22: 3871-3896.

Singh, T., Biswal, A., Mor, S., Ravindra, K., Singh, V. and Mor, S. (2020). A high-resolution emission inventory of air pollutants from primary crop residue burning over Northern India based on VIIRS thermal anomalies. Environmental Pollution. 266: 1-9.

Singh, T., Kaur, M. and Singh, G. (2021). Extent of adoption of happy seeder technology among the farmers of Punjab (India). Indian Journal of Extension Education. 57: 75-79.

Singh, Y., Singh, D. and Tripathi, R.P. (1996). Crop residue management in rice-wheat cropping system. Abstracts of poster sessions. Second International Crop Science Congress. National Academy of Agricultural Sciences, New Delhi, India. pp. 43.

Singh. S., Kingra, H.S. and Sangeet. (2013). Custom hiring services of farm machinery in Punjab: Impact and policies. Indian Research Journal of Extension. Education. 13: 45-50.

Tankiwala, A.K., Naik, R.M. and Patel, M.J. (2022). Farmers' awareness level about soil related issues and its causes. Gujarat Journal of Extension Education. 34: 120-123.

Udakwar, S. and Sarode, D. (2023). A study of generation and regulation of crop residue: Bioenergy. Bhartiya Krishi Anusandhan Patrika. 38: 267-275.

Yogi, V., Kar, A., Bhardwaj, S. and Mehla, V. (2015). Impact of zero tillage practices on economics of wheat cultivation in Haryana. International Research Journal of Agricultural Economics and Statistics. 6: 376-378.

Zaidi, S.T. (2021). Rice crop residue burning and alternative measures by India: A review. Journal of Scientific Research. 65: 132-137.