STUBBLE MANAGEMENT

HARNESSING EX-SITU OPTIONS AND MARKET MECHANISMS

Stubble Management: Harnessing Ex-Situ Options and Market Mechanisms

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'Punjab farmers possess an enterprising spirit; once they are shown the path and provided with a safety net during the initial phase, they will independently manage and sustain their efforts.'

– CS Grewal, Farmer

1. Introduction

Punjab, known as the 'Granary of India', is among the top three producers of food grain in the country, with over 11 million tonnes of rice and 16 million tonnes of wheat produced every year (Directorate of Economics and Statistics, 2016–2022; Ministry of Finance, 2024). The state relies heavily on the rice–wheat cropping pattern, wherein rice is cultivated during the *kharif* (summer) season and wheat during the *rabi* (winter) season. These two crops occupy over 80% of Punjab's total cropped area (Ministry of Agriculture & Farmer Welfare, 2020). To handle this large-scale crop harvesting, farmers have transitioned to using mechanical harvesters, leaving stubble on the ground. Moreover, as the next sowing cycle begins immediately, the farmers are left with a short window to manage the stubble. Consequently, farmers often resort to stubble burning, with more than 50% of the rice stubble burnt in Punjab in 2020 (Kurinji et al., 2021).

Figure 1: Reasons for stubble burning

To address stubble burning, the state and central governments have implemented various policies, including financial incentives, subsidised machinery, a ban on burning, and demand creation for stubble utilisation in thermal power plants (TPPs), industrial boilers, compressed biogas (CBG) plants, etc. The policies have been effective to some extent in controlling stubble burning. Although Punjab is yet to achieve its zero-burn target, there has been a 27% reduction in fire counts (Figure 2) from 2022 to 2023 (Punjab Remote Sensing Centre, 2024). At present, Sangrur, Firozpur, Bathinda, and Moga districts collectively account for over 40% of the total fire counts in Punjab.

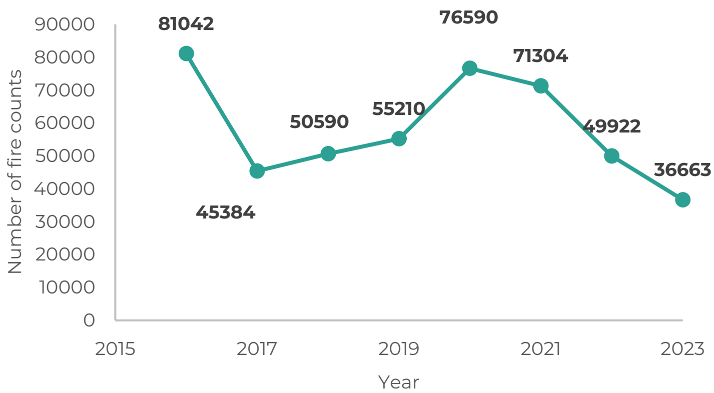

Figure 2: Fire counts in Punjab from 2015 to 2023 (kharif season)

Figure 3: District-wise fire counts (2023)

Impacts: Stubble burning has repercussions on health and environment. As per this study's estimations, $PM_{2.5}$ emissions[i] from stubble burning in Punjab in 2018 were 91 Gg at the end of the *kharif* season and 29 Gg at the end of the *rabi* season. Moreover, Gupta et al. (2017) and Singh et al. (2017) have linked stubble burning to increased respiratory diseases, while Mandal et al. (2004) and Abdurrahman et al. (2020) have reported that stubble burning decreases soil fertility.

Figure 4: Local impacts of stubble burning

[i] $PM_{2.5}$ emissions = Total area burnt × straw per unit area × emission factor of rice straw burning.

2. Control mechanisms

The stubble management options can be broadly classified as in-situ (managing stubble in the field) and ex-situ (removing stubble from the field and utilising it elsewhere) methods. Both the state and central governments have implemented several policies to support these strategies and have been setting ambitious targets, as shown in Figure 5. These policies include the 'Promotion of Agricultural Mechanisation for In-Situ Management of Crop Residue' scheme, under which custom hiring centres (CHCs) are being established (Punjab Pollution Control Board, 2024). Moreover, incentives and mandates are being given to industries adopting ex-situ options (Punjab State Council for Science & Technology, 2022; Ministry of Power, 2023b). Crop diversification is another option that encourages the cultivation of alternative crops, reducing rice stubble generation and eliminating the need for stubble management.

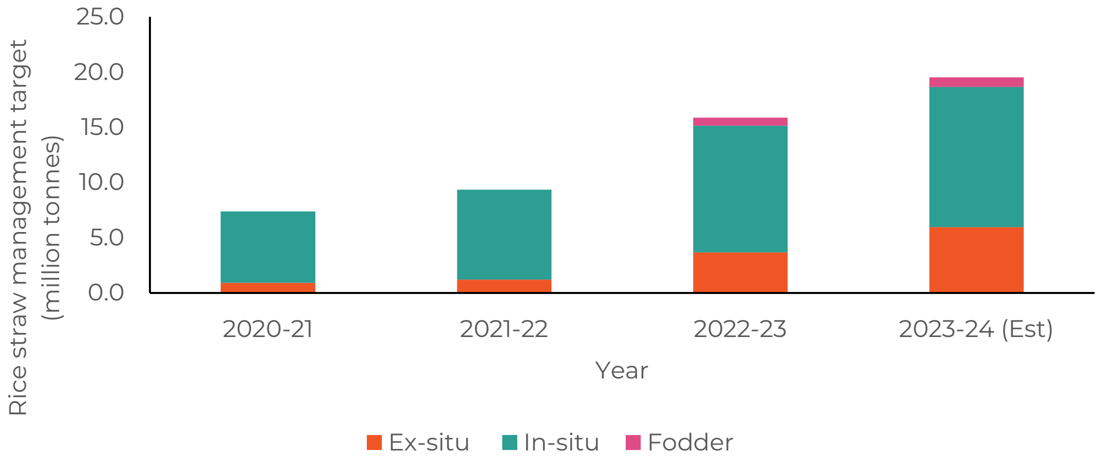

Figure 5: Rice straw management targets (excluding crop diversification)

(Source: Compilation from Punjab Pollution Control Board [2023, 2024a])

In-situ management

Mulching (spreading straw residues on the soil surface) and straw incorporation (mixing crop residues back into the soil) are the common methods for in-situ stubble management. Studies have indicated that incorporating straw into the soil increases wheat production by 58% and improves soil fertility by enhancing nutrient availability (Pachauri et al., 2023; Yadvinder, S. et al., 2004). Therefore, to support these activities, the government has introduced policies such as the Promotion of Agricultural Mechanisation for In-situ Management of Crop Residue in Punjab, Haryana, Uttar Pradesh, and the National Capital Territory of Delhi, providing financial assistance to procure in-situ machinery. The government has also been offering crop residue management (CRM) machines at a subsidy of 50% and has established CHCs to enhance the accessibility of these machines (Ministry of Agriculture & Farmers Welfare, 2023).

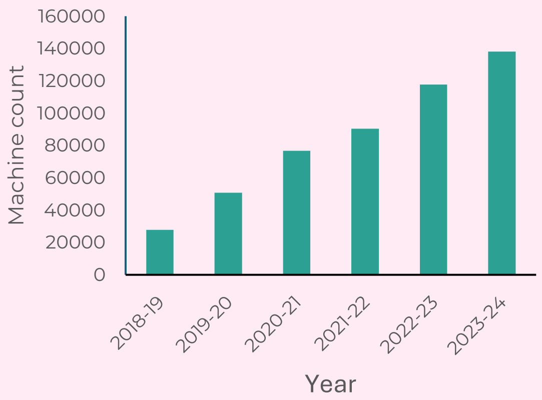

Figure 6: CRM machines supplied by the government (cumulative)

As per the Punjab Pollution Control Board (2024b), 1,38,022 CRM machines were deployed in various districts of Punjab as of the financial year (FY) 2023–24 (Figure 6). While the existing in-situ machines appear sufficient to manage the target set under in-situ options, issues such as limited uptake of rental machines from CHCs, delay in timely access to in-situ machines, and lack of awareness on standard operating procedures for in-situ machines have reduced the utilisation rate of these machines (Kemanth et al., 2024). Moreover, some of the machines (especially those issued years ago) may be in a state of disrepair, rendering them inoperable. Some farmers also opt for partial stubble burning even when using in-situ machines, believing it will reduce costs and help control pests (Kemanth et al., 2024).

Decomposing stubble in the field is also an in-situ option. Indian Council of Agricultural Research’s (ICAR's) Indian Agricultural Research Institute (IARI) developed the Pusa Decomposer to accelerate decomposition. However, its success has been hindered by insufficient awareness and doubts about its effectiveness (Sehgal, 2023).

Crop diversification

The major crops grown in Punjab are wheat, rice, sugarcane, maize, cotton, and vegetables (mainly potatoes), while crops such as mustard, fruits, tur, and gram are grown in smaller proportions. Although minimum support price (MSP, INR per quintal) is available for most of these crops, profitability remains a challenge due to factors such as market fluctuations and lack of assured procurement (Ministry of Agriculture & Farmers Welfare, 2024).

Conversely, the government ensures procurement of rice and wheat at MSP, making these crops reliably profitable. For example, in 2018–19, rice–wheat profits were INR 140,862/hectare compared with INR 137,051/hectare for cotton–wheat, INR 80,750/hectare for maize–wheat, and INR 85,062/hectare for rice–gram (Ministry of Agriculture & Farmers Welfare, 2019; Saini et al., 2022). Although sugarcane profits were higher (INR 176,683/hectare), sugarcane is not a viable solution due to its high water consumption (Gupta, 2023). Moreover, wheat and rice offer market stability and predictable incomes, unlike other crops that are subject to volatility.

In 2016, the Malerkotla block of Punjab's Sangrur district was chosen for vegetable cultivation under the agri-export zone (National Bank for Agriculture and Rural Development, 2017). Although it faced challenges such as timely power supply, it is a successful example of crop diversification (Singh, 2017).

The Punjab government initiated a crop diversification plan in 2013 to promote cotton and maize cultivation by subsidising cotton and maize seeds (Ministry of Agriculture, 2013). While there has been partial uptake with cotton–wheat being almost as profitable as rice–wheat, some farmers are reluctant to adopt cotton cultivation primarily due to crop failures in the recent past (Joshi, 2024). The government is targeting to expand its crop diversification plan to cover 0.3 million hectares in 2024 (Nibber, 2024). However, achieving this target could be challenging as the estimated area under cultivation for some crops has decreased. For example, the area under cotton cultivation decreased by 31% in 2023–24 (Cotton Association of India, 2024). The recent announcement of an incentive of INR 7,000 per acre for farmers adopting crops other than rice as part of the push for crop diversification could help reverse this decline (Vasdev, 2024).

2.1. Ex-situ management

Ex-situ management of rice stubble involves the collection and transportation of crop residue to various processing facilities for further use or conversion into pellets or briquettes (Figure 7).

Figure 7: Various forms of processed biomass: a) torrefied pellets, b) pellets, and c) briquettes

The government has recommended several ex-situ options to manage stubble; however, issues such as apprehensions surrounding the scalability of these options, supply chain constraints, and year-long availability of stubble continue to remain. Table 1 lists the most common ex-situ use cases for stubble management.

Table 1: Common use cases for ex-situ stubble management

<table>
<tr><th colspan="2">Use case</th><th>Description</th><th>Challenge</th><th>Resource required</th><th>Externality</th></tr>
<tr><td rowspan="4">Energy use</td><td>Fuel (pellets)</td><td>Conversion of stubble into pellets for co-firing in TPPs, brick kilns, and boilers</td><td>Low calorific value of stubble
Modification of boiler design</td><td>Minor costs (pelletisation, transportation, and boiler modification; AET BioMass, 2024)</td><td>Reduces reliance on fossil fuels, thereby lowering carbon emissions (pellets are carbon neutral; SAMARTH Mission, n.d.)</td></tr>
<tr><td>Bioenergy production</td><td>Gasification/combustion</td><td rowspan="3">High capital investment
Requires supply of stubble throughout the year</td><td rowspan="3">Substantial investment</td><td>Positive: Energy without fossil fuel, waste to wealth; Negative: Uses more water</td></tr>
<tr><td>CBG plant</td><td>Anaerobic digestion to produce bio-CNG</td><td>Creates multiple revenue streams (bio-CNG, manure, etc.)</td></tr>
<tr><td>Bioethanol plant</td><td>Ethanol production through fermentation</td><td>Reduces reliance on fossil fuel; by-product can be used as animal feed</td></tr>
<tr><td rowspan="3">Non-energy use</td><td>Biochar</td><td>Production from biomass via pyrolysis</td><td>Application of biochar in India is limited (Venkatesh et al., 2018)</td><td>R&D on biochar uses in India</td><td>Enhances soil fertility; carbon sequestration</td></tr>
<tr><td>Alternative uses</td><td>Used in mushroom cultivation and paper industries; as insulation, packaging, and construction materials</td><td>Requires heavy water usage and technological knowledge</td><td>Requires heavy processing units and new markets</td><td>Reduces dependency on wood, plastic, etc.</td></tr>
<tr><td>Composting</td><td>Decomposing rice stubble to produce compost</td><td>Labour-intensive
Seasonal availability</td><td>Needs separate space</td><td>Enhances soil fertility; reduces dependency on chemical fertiliser</td></tr>
</table>

Targets: According to the Punjab Pollution Control Board (2024a), rice stubble is intended for use in industries such as CBG plants, biomass-based power plants, and brick kilns. Earlier, brick kilns were one of the largest consumers of rice straw; however, since the introduction of a mandate by the Ministry of Environment, Forest, and Climate Change (MoEFCC) in 2019 for the use of fly ash in brick manufacturing, straw consumption in brick kilns has drastically reduced (Bhattacharyya et al., 2021; Dutta et al., 2022). One of the possible reasons is the requirement of different production processes and materials for fly ash bricks. Figure 8 illustrates the targets for various ex-situ options. With the biomass utilisation policy by the Ministry of Power (2021) mandating 5% co-firing in TPPs (0.7 million tonnes), the Punjab government's requirement of 20% pellet usage in brick kilns (0.9 million tonnes), and the construction of new bio-CNG plants (1 million tonnes), the state is projected to consume nearly 5.96 million tonnes of straw through ex-situ options by 2024 (Chaba, 2023; Punjab Pollution Control Board, 2024a).

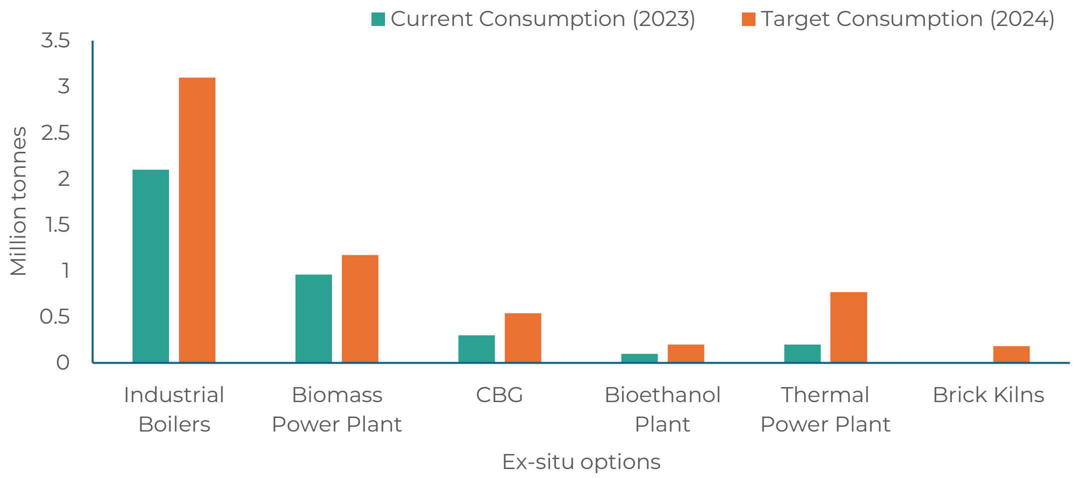

Figure 8: Targets set for ex-situ options for 2024

Effective utilisation of straw in the above options relies on the following three key components in the supply chain:

- Supply of straw from the farmers,
- Robust infrastructure for storing and transporting stubble to the end users, and
- Established markets to facilitate the transaction between farmers and end users.

Supply chain options: The steps involved in the supply chain for crop residue is depicted in the figure below.

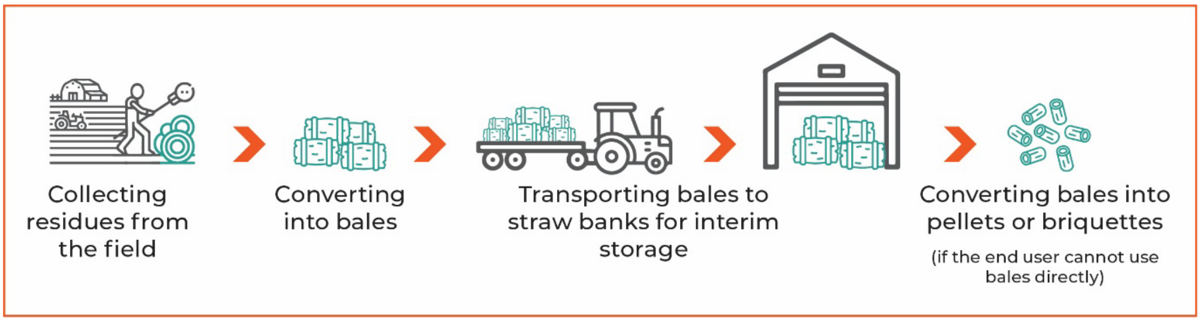

Figure 9: The supply chain for crop residue

The process involved and unit cost (INR/tonne) of all options are provided in Figure 10.

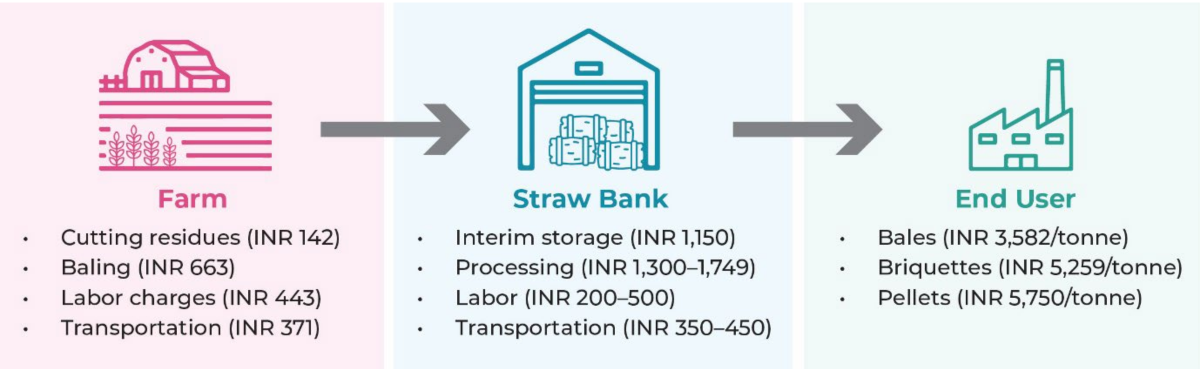

Figure 10: Supply chain stages and costs involved (Source: Kurinji et al., 2021 – adjusted for inflation)

Farmers and aggregators (intermediaries who collect, process, and deliver stubble to end users at a price) primarily use balers to transform stubble into bales. While not enough balers are currently available, a recent initiative by the Punjab government to assemble German balers locally is expected to narrow the gap. The stubble bales are then transported either to the end user or to a straw bank. As provided in the figure above, transporting stubble directly from the farm to the end user without any interim storage would cost approximately INR 1,620/tonne (adjusted for inflation; Kurinji et al., 2021). Similarly, transporting stubble in the form of bales, briquettes, and pellets to the end user would cost INR 3,582, 5,259, and 5,750 per tonne, respectively. Currently, only pellets designated for use in power plants have a well-defined framework by the Ministry of Power (2023a) for benchmarking prices, which includes pellet characteristics such as moisture content and gross calorific value. Establishing a similar comprehensive framework for other stubble products would be highly beneficial.

Farmers rely heavily on biomass aggregators to clear their fields. Aggregators incur the costs of operations and machinery and may pay a small amount to the farmers for the stubble. However, only a small number of farmers adopting ex-situ options receive compensation, while most end up paying to have their fields cleared, which disincentivises this alternative to stubble burning (Kemanth et al., 2024). To encourage farmers to adopt ex-situ options, the government should ensure that farmers (and if needed, aggregators) are adequately compensated by considering the cost incurred in each stage of the process.

Straw banks and pelletisation units: The state needs around 1,320 straw banks[ii] to meet the targets for ex-situ management. However, there are few straw banks currently, primarily concentrated in Amritsar, Barnala, Bathinda, Fazilka, Firozpur, Ludhiana, Mansa, Moga, Patiala, and Sangrur. Brick kilns, TPPs, and other selected industries need stubble in the form of pellets for co-firing (Ministry of Power, 2021). Currently, the state has 13 pelletisation units and is expected to add 21 units by 2024, increasing stubble processing capacity to 0.7 million tonnes (Punjab Pollution Control Board, 2024a). However, the demand for pellets exceeds 3 million tonnes. Hence, there is a pressing need to establish at least 130 pelletisation units ideally situated near TPPs and brick kilns.

[ii] Straw banks required = Targeted straw management with ex situ options/straw bank capacity (4,500 tonnes).

3. Establishing an efficient stubble market: Key strategies and government actions

A key hurdle to the effective use of ex-situ options for stubble management is the lack of an efficient market connecting agricultural stubble from farms with end users. Several critical components need to be integrated for this purpose, including ensuring sufficient supply and demand, developing transportation and storage infrastructure, and improving the regulatory framework. The following section suggests actions the government can take to streamline and optimise the stubble exchange process.

3.1. Regulatory framework

Farmers are crucial to the supply chain, and without their cooperation, the entire supply chain is at risk. Here are some policy recommendations the government could implement to enhance supply and demand.

3.1.1. Enhancing supply

Incentives for farmers: Farmers spend around INR 1,500–1,800 per tonne on cutting, baling, and transporting straw to straw banks, either directly or through aggregators. Subsidising these costs could reduce the financial burden on farmers, especially if the cost incurred by the farmers to remove stubble from the field is paid upfront.

Focused collection and supply: Farmers with more than 4 hectares of land account for approximately 66% of Punjab's total agricultural area (Figure 11). Stubble burning tends to be more prevalent among medium- and large-scale farmers than among small-scale farmers (Kemanth et al., 2024). Hence, efforts for ex-situ stubble management should focus on these medium- and large-scale farmers.

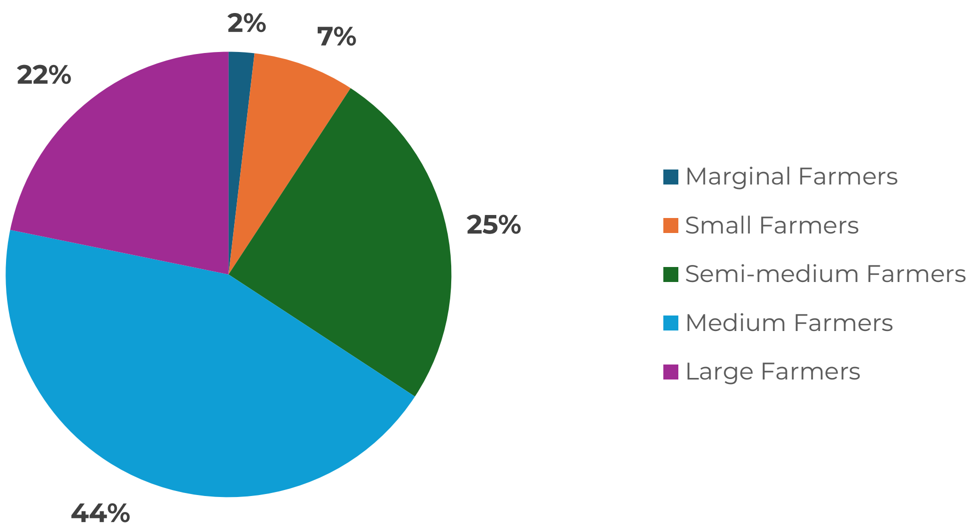

Figure 11: Land holding pattern in Punjab

3.1.2. Stimulating demand

Prioritise key industries: Industries such as CBG and biomass-based power plants need a continuous supply of stubble to operate efficiently. Therefore, aggregators should prioritise supplying stubble to these existing industries. Demonstrating that the current supply chain network can meet the requirements of these plants will pave the way for setting up new CBG, biomass-based power plants, or other ex-situ industries. Subsequently, attention can shift to industries such as brick kilns, TPPs, and industrial boilers that need stubble in the form of pellets and can function even if stubble is not available. The government should also ensure that industries requiring stubble must place their order well in advance.

Long-term contracts: To utilise stubble as raw material, long-term contracts should be secured with industries such as CBG plants, TPPs, and other industrial boilers. This will ensure a reliable market and consistent demand for stubble, increasing the confidence of farmers in stubble processing and avoiding stubble burning.

Innovation grants and other support for start-ups: The India Innovation Growth Programme needs to be promoted to encourage start-ups that use stubble as raw material. Moreover, collaboration and networking events should be conducted regularly to increase the visibility of these start-ups and facilitate knowledge sharing. As products made from stubble are typically more expensive than their conventional counterparts, the government should provide incentives or subsidies to industries that utilise stubble-based products. Tax benefits can also be offered to help these start-ups stay competitive in the market.

Apart from these measures, the government should establish and promote dedicated marketplaces to commercialise stubble-based products developed by start-ups. For example, start-ups such as Dharaksha Ecosolutions, Takachar, GreenJams, Craste, and Kriya Labs have successfully converted stubble into alternative products with support from private investments and government funding programmes. A few of these start-ups are also producing cost-competitive products, highlighting a promising potential for stubble-based ventures. The establishment of more incubation centres and specialised markets for stubble-based products can foster the growth of more such start-ups, increasing the demand for stubble.

3.2. Establishing adequate infrastructure

A robust supply chain network is essential for addressing the challenges associated with ex-situ stubble management. Key infrastructure components include storage facilities, collection centres, pelletisation units, and machinery facilitating goods movement.

Setting up straw banks and pelletisation units: Public–private partnerships (PPPs) should be explored for setting up straw banks. These partnerships can leverage private sector resources and public sector support to build necessary infrastructure (such as land, power supply, labour, and logistics) for straw collection, storage, and processing.

Key demand areas: There are several use cases of stubble. Figure 12 highlights locations of key sectors that can utilise stubble in the form of pellets. The dark red colour represents industrial areas where the demand for stubble exceeds 0.1 million tonnes/year. The government could prioritise strengthening the supply chain infrastructure in districts with a higher concentration of industrial clusters and brick kilns, such as Patiala, Bathinda, Rupnagar, Mansa, Tarn Taran, Amritsar, and Sangrur, before expanding to other districts. Moreover, pelletisation units should be located near the identified clusters.

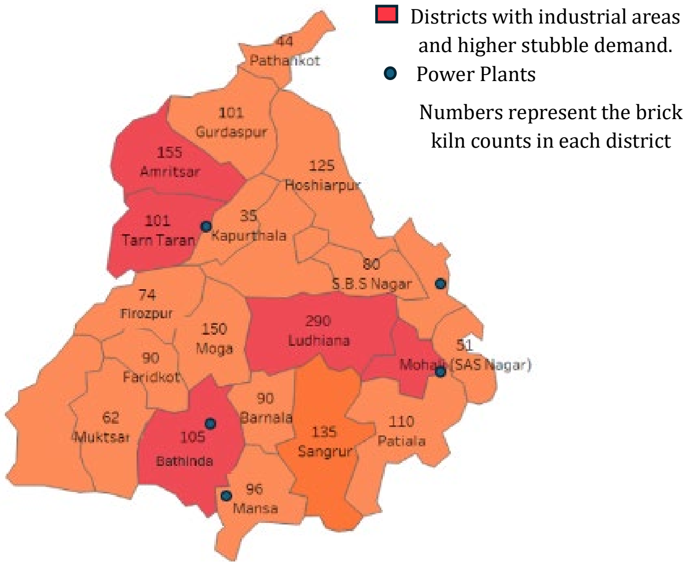

Figure 12: Key demand areas for pellets

3.3. Setting up new industries: Feasibility and cost analysis of ex-situ stubble management methods

This study evaluated the financial feasibility of different ex-situ stubble management options in Punjab with the goal of identifying the most suitable one. The supplementary information provided in Appendix (Table A1) outlines their costs, the key factors enabling their success, and the maximum feasible stubble consumption for each method. Each of these ex-situ options has its own advantages and limitations. Usage of stubble pellets in TPPs (within the 5% co-firing mandate), industrial boilers, and brick kilns does not require heavy investment or significant modifications, unlike in capital-intensive alternatives such as CBG plants or biomass-based power plants. However, the scalability of stubble usage is limited for brick kilns, TPPs, and industrial boilers as the stubble consumption is limited to the existing capacity and machinery requirements. CBG plants and biomass-based power plants can be set up wherever needed. However, these industries rely completely on stubble and may incur losses if stubble availability is inconsistent. Financially, most of the ex-situ options offer a positive return although some may require government support such as viability gap funding and feed-in tariffs.

Successful stories from several countries in Europe, the United States, and the United Kingdom have revealed how co-firing biomass has significantly reduced their carbon footprint. For instance, the Drax power station in England, with a capacity of 2.6 GW, transitioned from coal to biomass (wood pellets) after retiring 1.29 GW capacity from coal in 2021 (TMI Staff & Contributors, 2021). This transition underscores the viability of large-scale biomass utilisation. Moreover, one of the four 120 MW units at the Krakow-Leg power station, Poland, has substituted 35% of its hard coal fuel with biomass, including wooden biomass and agro-biomass pellets (Fortum, n.d.). This co-firing could reduce NO_x emissions by 20%–30%, highlighting the environmental benefits of biomass integration.

Datta et al. (2020) has suggested that gasification of biomass can be used as an alternative to consume rice stubble. Utilising crop residues as fuel for biomass gasifiers can support tri-generation applications, including electricity, agro-processing, and decentralised cold storage at the village level. This provides farmers with an alternative to shift to horticulture crops, addressing the issue of limited local cold storage. A 250 kWe biomass gasifier plant can utilise about 2,000 tonnes of rice straw annually, supporting a 50-tonne refrigeration cold storage facility alongside electricity production (Datta et al., 2020).

4. Recommendations

The strategic recommendations to address the complex challenges of stubble management effectively are discussed below.

4.1. Adopting a balanced approach to in-situ and ex-situ management

While Punjab appears to have sufficient in-situ machinery, there is a significant gap in supporting infrastructure for ex-situ options. In-situ management techniques such as mulching may help improve soil fertility, but ex-situ options offer several positive externalities, including job creation, reduced reliance on fossil fuels, efficient stubble utilisation, and additional revenue for farmers. **A balanced approach utilising both in-situ and ex-situ options is recommended for optimal stubble management. Greater attention should be directed towards developing ex-situ management as a viable alternative.**

4.2. Strengthening machinery and infrastructure

1) **Prioritising locations:** Key industrial areas such as Bathinda, Mansa, and Patiala need easy access to balers; therefore, access to balers should be preferred over Happy Seeders and Super Seeders in such areas.
2) **Increasing baler usage:** Mandate and monitor the use of subsidised balers at designated farms to ensure effective baler utilisation.
3) **Increasing the number of straw banks and pelletisation units:** Punjab needs at least 1,320 straw banks spread across the state and 165 pelletisation units primarily located near TPPs, brick kilns, and industries to process the stubble targeted by ex-situ options.

4.3. Stimulating supply

1) **Engaging selected farmers:** While all farmers should manage stubble, targeting those with land greater than 4 hectares for ex-situ management leverages economies of scale and maximises resource allocation. Larger farms are better equipped to invest in and implement these practices effectively.
2) **Incentivising over penalising farmers:** Collecting and transporting stubble to the nearest straw bank costs INR 1,500–1,800/tonne. The government should ensure that farmers are adequately compensated for the time and amount they invest.

4.4. Driving demand

1) **Setting up new industries to use stubble:** For scalability, industries such as CBG plants should be promoted. For ease of implementation, stubble use in industrial boilers, brick kilns, and TPPs should be prioritised.

2) **Exploring alternative revenue streams:** Incorporating carbon-credit-based mechanisms into stubble management can ensure an additional value stream. Moreover, creating markets for alternative products such as manure will help industries become more profitable.

3) **Promoting start-ups**: Setting up incubators for start-ups and creating specialised markets for stubble-based products would be helpful.

4) **Establishing contractual agreements:** This will ensure that farmers receive guaranteed payments for their stubble and end users get a reliable supply, facilitating smooth and efficient stubble management. The contract should be made on an annual basis or flexible duration as long-term contracts may restrict the entry of new players.

4.5. Other recommendations

1) **Conducting public awareness campaigns:** Awareness campaigns should be conducted to educate farmers about the ill effects of stubble burning and benefits of crop residue management.

2) **Advancing research:** Support mechanisms should be established for research projects aimed at reducing crop residue. This includes creating a common pool for funding collaborative R&D to innovate in this space.

3) **Simplifying the process of renting machines from CHCs:** The application and approval procedures for renting out machines from CHCs should be streamlined to ensure that farmers can easily access and benefit from them without facing cumbersome and complex processes.

4) **Benchmarking price for agricultural residue products**: Use cost-based pricing to establish a minimum price for stubble products.

5) **Establishing monitoring and enforcement agencies**: Agencies for monitoring stubble collection, storage, and supply to industries need to be set up. Moreover, joint inspections by central and state agencies should be conducted to ensure that regulations are being followed across all areas (collection centres, farmlands, TPPs, etc.).

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Appendix

Table A1: Cost analysis of common ex-situ options for stubble consumption

Option	Cost (INR)	Financial metrics[iii]	Implement ability	Key enabler/ requirement	Stubble consumed at 100% utilisation[iv] and scalability potential
Co-firing in TPPs	Landed cost of coal: INR 6,241/metric tonne (PSPCL, 2024) Landed cost of biomass pellets: INR 9,000/metric tonne (Aggarwal et al., 2023)	INR 0.1 to INR 0.12 per unit increase in levelised cost of electricity (LCOE)	High (pellets can easily be used as a fuel; TPPs are located only at a few locations; use of existing infrastructure)	Pelletisation units Up to 10% co-firing should not be a problem (Tanwani, n.d.)	Co-firing at 5%–7% can lead to usage of 0.81 to 1.14 million tonnes of stubble **Scalability**: Can be expanded to other TPPs, but LCOE may increase with the distance from the stubble source
Biomass-based power plant	Capital cost: INR 6 crore /MW Fuel cost: INR 3,000/tonne of stubble	LCOE of biomass plants: INR 8–9/unit TPP plants: INR 4.5–5/unit	Moderate (need for setting up plants, continuous supply of biomass)	Feed-in tariffs Viability gap funding	1 million tonnes (Punjab Energy Development Agency, n.d.) **Scalability:** Setting up new plants is resource-intensive but feasible

[iii] Financial analysis and cost sensitivity by varying fuel costs while keeping other expenses constant.
[iv] Total available plants * Stubble consumed per plant at the maximum feasible utilisation.

Option	Cost (INR)	Financial metrics[iii]	Implement ability	Key enabler/ requirement	Stubble consumed at 100% utilisation[iv] and scalability potential
CBG plants	Capital cost: INR 30 crore Capacity: 40 tonnes/ day Bio-CNG: INR 54/kg Manure: INR 5,000 /tonne	Profit: INR 1.18 crore/year	Moderate (need for setting up plants, continuous supply of biomass)	Market for manure Fermented organic manure (FOM) and liquid organic manure (LOM)	0.5 million tonnes (Yadav, 2024; India Infrahub, 2022) **Scalability:** Setting up new plants is resource-intensive but feasible and profitable
Usage in industrial boilers	Cost of stubble: INR 2,000 /tonne (Sharma, 2023) Cost of conversion: 15%–30% of the rice straw boiler cost	Payback period: 1.8 years	Moderate to high (boiler modification is required, supply of biomass)	Pelletisation units	If 50 industries switch to stubble-based boilers, they will collectively use 3.75 million tonnes of stubble annually, based on an average rice straw consumption of 70–75 kilotonne per industry. **Scalability:** Only existing industries can be converted
Bioethanol plants	Capacity: 100 kL/day	Cost of production: INR 93/L (Zhou et al., 2021) Purchase price of 2 g ethanol: INR 65.61/L (National Sugar Institute, 2022)	Moderate (need for setting up plants, continuous supply of biomass)	Viability gap funding	0.2 million tonnes with the current capacity in Punjab **Scalability:** Setting up new plants is resource-intensive but feasible
Usage in brick kilns	Cost of coal: INR 15,000/ tonne Cost of pellet: INR 6,000/ tonne	Upon adopting 20% co-firing, fuel cost reduces by 8%–10% and operating cost decreases by 4%–6%	Very high (pellets usable with minor adjustments; widespread kiln locations)	Decentralised pelletisation unit near brick kiln locations Capture emissions	0.82 million tonnes of stubble if all brick kilns adopt 20% co-firing **Scalability**: Only existing industries can be converted

Preference Low — Medium — High

(Source: CSTEP analysis and compilation)

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