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Is Ex-situ Crop Residue Management a Scalable Solution to Stubble Burning?

A Punjab Case Study

L. S. Kurinji and Sankalp Kumar

Report | January 2021

In 2018, 65 per cent of paddy residue (nearly 13 million tonnes) was set on fire in the fields of Punjab, choking the air in the entire Indo-Gangetic plains (Ministry of Agriculture & Farmers Welfare 2018).

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We would like to thank our reviewers—Prof. Vish Krishnan, Professor & Chair, University of California, Priya Shyamsundar, Lead Economist, The Nature Conservancy, Mohit Sharma, Associate Counsellor, CII-ITC Centre of Excellence for Sustainable Development, Udhaya Kumar V, Senior Research Analyst, Center for Study of Science, Technology and Policy Rishabh Jain, Manager, Market Intelligence, CEEW Centre for Energy Finance and Niti Gupta, Programme Associate, CEEW—for providing critical feedback and comments to refine this report. We extend out thanks to Karthik Ganesan, Research Fellow, CEEW, and Tanushree Ganguly, Programme Associate, CEEW, for providing us with valuable guidance throughout the study.

We sought out entrepreneurs in the supply chain— Monish Ahuja, Lt. Col. (Retd.), Promoter and Managing Director, Punjab Renewable Energy Systems Private Limited; Sukhmeet Singh, Co-Founder, A2P Energy Solution Private Limited; Nitin Gupta, Director, Farm2Energy; Aayushi Aggarwal, Co-Founder, RY Energies; and Naresh Kumar, Co-Founder, Shri Rishabh Travels—for information on supply chain management of crop residue in Punjab and they were gracious enough to share data and details we needed, for which we express our sincere gratitude.

Finally, we thank our Outreach team, particularly Alina Sen, Communications Specialist, for her guidance and support at the publication stage and her efforts to ensure that the report meets the CEEW's quality standards.

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A policy researcher at The Council, Kurinji's research focuses on the use of alternative methods of monitoring air quality and activities that cause pollution. She also plays an active role in providing tangible solutions to address regulatory challenges in implementing clean air policies. She holds a bachelor's degree in energy and environmental engineering from Tamil Nadu Agricultural University, Coimbatore. She is an Indian Green Building Council (IGBC) accredited professional.

"Though ex-situ crop residue management appears like an attractive proposition for Punjab's stubble burning crisis, the supply chain of the system is still an issue because of its economics. The sector needs optimisation. Through this report, we identify tangible solutions to support the supply chain, thereby to scale up ex-situ management in the state."

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A research intern at The Council, Sankalp researches on ways to redress air pollution. He believes even a small step to solving the crisis of air pollution is, a giant leap towards creating sustainable societies. He is pursuing environmental engineering from the Delhi Technological University and prior to CEEW, he was a research intern at the Centre for Fire, Explosive and Environmental Safety (CFEES), a part of Defence Research and Development Organisation (DRDO).

"Crop residue burning has been an age-old problem vitiating air quality in the Indo-Gangetic plains; it is high time we look towards solutions to solve this crisis. Ex-situ management of residue offers a practical solution to the problem. This report will assist the stakeholders in scaling up the ex-situ management of crop residue in Punjab."

Since manual harvesting is labour- intensive and costs time and money, farmers opt for mechanised harvesting using the combine harvester. The machine cuts only the top portion of the crops leaving standing stubble in the field.

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Image: iStock

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Acronyms

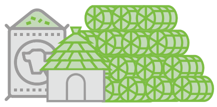
A2P	Agri2Power
CEA	Central Electricity Authority of India
CHCs	custom hiring centres
CIL	Coal India Limited
CNG	compressed natural gas
COVID-19	disease caused by novel coronavirus, first detected in 2019
CSERC	Chhattisgarh State Electricity Regulatory Commission
eNAM	National Agriculture Market
EOI	expression of interest
INR	Indian rupee
IREDA	Indian Renewable Energy Development Agency Ltd
LCA	life-cycle assessment
MoES	Ministry of Earth Sciences
MoU	memorandum of understanding
NAAQS	National Ambient Air Quality Standards
NABARD	National Bank for Agriculture And Rural Development
NREBPL	Neway Renewable Energy Bathinda Private Limited
NRSE	New and Renewable Sources of Energy Policy
NTPC	National Thermal Power Corporation
PAU	Punjab Agricultural University
PEDA	Punjab Energy Development Agency
PM	particulate matter
PRESPL	Punjab Renewable Energy Systems Pvt. Ltd
PSCST	Punjab State Council on Science and Technology
PSPCL	Punjab State Power Corporation Limited
SAFAR	System of Air Quality and Weather Forecasting And Research
SCM	supply chain management

Collection of crop residue is a labour intensive task and is a major cost in the crop residue supply chain.

Image: A2P Energy

Executive summary

Agriculture and allied sectors contribute around 16.5 per cent to India's GDP and employs nearly half of the country's workforce (PRSIndia 2020). A massive amount of crop residue (~683 million tonnes) is generated during crop production in the net sown area of 140 million hectares across the country. While farmers use crop residue as animal fodder and for roof thatching, a significant portion (178 million tonnes) is left unused ever year (TIFAC and IARI 2018). Further, the unhealthy practice of on-farm burning of agricultural residue to clear land for the next crop, primarily in the north-western states of India, contributes to alarming levels of air pollution in the Indo-Gangetic plains.



While farmers use crop residue as animal fodder and for roof thatching, a significant portion (178 million tonnes) is left unused every year in India

Farmers in Punjab, where 20 million tonnes of paddy residue is generated every year during the Kharif season (Ministry of Agriculture & Farmers Welfare 2018), face an unenviable task of clearing this residue in a short window of 15–20 days. This reduced timeframe is an offshoot of the *Punjab Preservation of Subsoil Act (2009)*, implemented to save groundwater by mandatorily postponing the transplanting of paddy from April–May to beyond 10 June (Jain 2019). In 2018, 65 per cent of paddy residue (nearly 13 million tonnes) was set on fire in the fields of Punjab, choking the air in the entire Indo-Gangetic plains (Ministry of Agriculture & Farmers Welfare 2018). The System of Air Quality and Weather Forecasting And Research (SAFAR) under the Ministry of Earth Sciences (MoES) estimated that paddy stubble burning in Punjab and Haryana contributed 40–45 per cent to Delhi's air pollution during peak burning days in 2019 (Press Trust of India 2019).

The courts have come down heavily on stubble burning, forcing the state and central governments to initiate measures to clamp down this practice in Punjab, Haryana and Uttar Pradesh. One such effort was through the New and Renewable Sources of Energy (NRSE) policy 2019, wherein the Punjab government encourages setting up of biomass power generation units and production of biofuels (bio-compressed natural gas [CNG], bio-ethanol, and bio-diesel) using biomass (mainly rice straw) as feedstock. As of September 2020, Punjab has 11 operational biomass power plants, with an aggregate capacity of 97.5 MW, in which 0.88 million tonnes of paddy straw are consumed annually (Chaba 2020b). In 2018, the central government reported that 1.10 million tonnes of paddy residue (5.5 per cent of total residue generated) were used in various ex-situ methods such as in paper/cardboard mill and biomass power projects (Ministry of Agriculture & Farmers Welfare 2018).

Ex-situ residue management methods such as biomass power plants and biofuel projects offer an attractive option of managing the excess crop residue generated. Therefore, to ensure sustainable use of crop residue, Punjab government is inclined to sign memoranda of understanding (MoUs) with private players to set up more biomass-based projects in the state. An investment of INR 4.45 to 6 crore per MW is needed for biomass power plants (Central Electricity Regulatory Commission 2019). But due to the lack of assured biomass supply, the private sector is not finding it economically viable to invest in additional biomass plants. To ensure a reliable supply of biomass to the end-user, the Punjab government needs to create a dense network of collection centres for effective supply chain management (SCM).

Entities involved in SCM facilitate the fast clearing of residue from the field to reach the end-user. Given the voluminous nature and seasonal availability of the crop residue, its handling and on-time delivery becomes a central issue as it requires a vast workforce, heavy vehicles for logistics and extensive storage infrastructure. In addition, as crop residue has lower energy density,[1] it is subjected to densification processes such as baling, briquetting, and pelletisation, which adds to the feedstock supply cost (J. Singh, Panesar, and Sharma 2010). Therefore, entrepreneurs in the supply chain find the economics of handling crop residue unattractive.

Pushed by an interest to understand the economics involved in the supply of biomass to end-users in Punjab, we undertook this study. We interviewed prominent firms involved in ex-situ SCM namely Punjab Renewable Energy Systems Private Limited, A2P Energy Solution Private Limited, Farm2Energy, and RY Energies in Punjab to chart the various steps (Table ES 1) involved and computed the delivered cost of paddy residue from the farm to the end-user. From these interviews, we have gathered insights on the delivered cost of various types of biomass products like bales, briquettes, and pellets to end-users. We further investigate the viability of the use of paddy residue in coal-fired power plants to supplement the use of coal in the state.

Table ES1 Supply chain of crop residue for ex-situ management

Residue collection	First-mile transportation	Interim storage (Optional)	Biomass processing (Optional)	Last-mile transportation
Paddy residue is chopped off from the field, collected, and densified into bales for smooth transportation.	The bales are loaded in a low-bed trolley/trailer and delivered to the nearest straw bank.	The bales are unloaded and stacked at the straw bank. This stage is optional as biomass can directly be supplied to end-user, which would eliminate storage cost and other costs associated with it.	These bales are further densified into briquettes or pellets based on end-users' requirement.	The bales or processed briquettes/pellets are dispatched to the end-user in a truck.
Farm to straw bank		Straw bank to end-user		

Source: Authors' compilation

1. The density of loose paddy straw, collected directly from the field, can range from 13 to 18 kg m^{-3} in dry matter (dm). The density of round paddy straw bale with a 70-cm length and 50-cm diameter range from 60–90 kg m^{-3} dm. The density of rice straw briquettes with a 90-mm diameter and 7- to 15-mm thickness is 350–450 kg m^{-3} dm. The density of rice straw pellets with an 8-mm diameter and from 30 to 50 mm in height is 600–700 kg m^{-3} dm (Van Hung et al. 2020).

Key findings

We summarise our findings on the delivered cost of paddy residue, optimum distance, and different forms of crop residue used for transit in the following. To calculate the delivered cost of biomass for the end-user, we divided the supply chain into two parts: farm to straw bank and straw bank to end-user (Table ES1).

Farm to straw bank

For computing expenses incurred for residue transportation from farm to the straw bank, we consider the rental cost of machinery (such as chopper/cutter-cum-spreader, baler, and raker), labour, and fuel required for cutting and baling of paddy residue, loading and unloading cost of bales at farm and straw bank, and transportation charges for carrying bales from farm to straw bank (Table ES1).

- The transit of paddy residue in the form of bales for a distance of 15 km from farm to straw bank typically costs INR 1,330 per tonne of bale (Figure ES1). Out of this, the cost associated with the cutting and baling of residue entails 50 per cent of the procurement cost.
- In most cases, SCM entities offer support by providing customised farm implements like raker and baler, needed for residue collection, as individual farmers do not maintain an inventory of such implements needed for ex-situ management. A few entities make use of an 'on-demand' model to locally source the farm implements from custom hiring centres (CHCs) or large farmers and provide those implements 'on demand' to individual farmers.

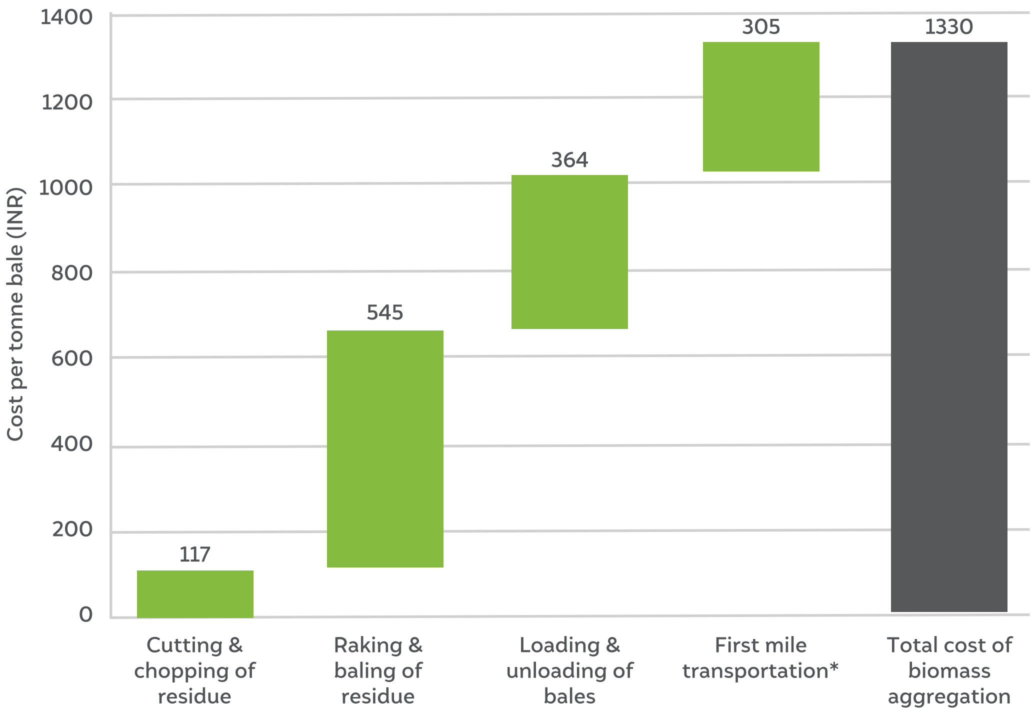


Figure ES1
Raking and baling cost is the highest in the aggregation of crop residue from farm to the straw bank

Source: Authors' analysis ;

*An optimum distance of 15 km between farm and straw bank is considered.

Straw bank to end-user

For costs incurred to transport farm residue from straw bank to end-user, we consider biomass conversion cost (briquetting and pelleting cost), loading and unloading cost at the straw bank and end-user, respectively, and transportation charges. We take into account three forms of biomass transported to the end-user — bales, briquettes and pellets. Both briquettes and pellets can be used in boilers and stoves. But considering their different sizes, briquettes are preferred in large and medium-scale boilers, while pellets are widely used in small-sized devices, such as pellet stove, furnace, and cooking range (The AGICO 2020). As briquette and pellets are preferred over bales because of their increased energy content in industries and power plants, we also estimate and compare the delivered cost per 5,000 Mcal of bales with briquettes and pellets.

Table ES2
Delivered cost of biomass per tonne to the end-user located at a distance of 50 km

Fragments	Components	Bale (INR)	Briquette (INR)*	Pellet (INR)*
Residue collection + first-mile transportation	Residue cost	1,351	1,757	1,757
Interim storage (optional)	Storage cost	880	1,144	1,144
Biomass processing (optional)	Biomass processing cost (briquette/pellet)	NA	1,034	1,437
Final transportation	Transport charges	347	250	250
	Loading and unloading cost	364	135	135
Total cost (INR/tonne)		**2,942**	**4,319**	**4,719**
Total cost (INR/5,000 Mcal)		**5,979**	**6,013**	**6,626**

Source: Authors' analysis

*About 1.3 tonne of residue is required to produce 1 tonne of briquette/ pellet. Additional cost of collection, transportation and storage of 0.3 tonnes of residue for every tonne of briquette and pellets has been added to briquettes and pellets resulting in the variation of collection, first mile transportation and storage cost between the three forms of biomass.

- Interim storage of the crop residue in straw banks assumes importance, given the limited span of 15–20 days available for sowing the next crop. A typical straw bank is spread over an area of 10–15 acres and can hold up to 10,000–15,000 tonnes of paddy residue. The storing cost constitutes 20–30 per cent of the total delivered cost of biomass.

- Transporting baled residue to the end-user beyond 50 km entails a high delivered cost, which may not be viable for companies engaged in the supply chain. Dispatching bales over a distance of 50 km incurs a total delivered cost of INR 2,950 per tonne of bale (Table ES2).

- Several studies have identified that densifying biomass in the form of briquettes or pellets would decrease the transportation cost (Balingbing et al. 2020; Possidônio et al. 2016). However, our analysis indicates that the high cost paid for briquetting and pelletising significantly eats into the benefits of reduced transportation cost of the densified residue.

- Dispatching briquettes over a distance of 50 km costs INR 4,320 per tonne delivered. But dispatching pellets over the same distance works out to a total delivered cost of INR 4,720 per tonne (Table ES2).

2. The two thermal power plants operating on coal in Punjab require 11.34 million tonnes of coal per annum (Government of India and Government of Punjab 2016)

- The high cost of pelleting makes transporting pelletised residue the costliest among all the options available. Supply chain entities concur with this observation. In most cases, SCM entities prefer to transport residue in the form of bales to avoid the high investment needed for biomass processing. However, biomass bales have limited end-use applications. They are used as packaging material, as raw material in cardboard and paper industries, in animal bedding, and in biochar and biogas production. For other end uses that require densified biomass, the end-user needs to invest in processing bales to briquettes or pellets.

- Co-firing 10 per cent of biomass pellets with coal in coal-fired power plants in Punjab[2] would require 1.47 million tonnes of paddy residue annually, which would account for nearly 7.4 per cent of paddy residue generated in Punjab. The delivered cost of biomass pellets per 5,000 Mcal within a radius of 50 km of the power plant is economical compared to coal. Beyond 50 km, the cost increases significantly.

- The delivered cost of briquettes per 5,000 Mcal is economical up to a distance of 145 km. Industries that consume coal for heating applications should explore the prospect of locally sourcing biomass briquettes within the state, as it will reduce their operating cost.

Key recommendations to support supply chain management of crop residue

Based on our assessment and consultations with prominent stakeholders, we recommend the following strategies for better management and scaling up the ex-situ use of crop residue.

- **Establish a dense network of straw banks and ex-situ supply chain ecosystem**

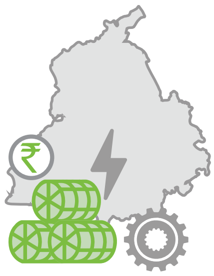
  Sourcing of crop residue for ex-situ use, in our estimates, is found to be financially viable for SCM entities when the crop residue collection point is located within 15 km and end-user is situated within 50 km. Hence, a dense network of straw banks needs to be created for streamlining the supply chain. Private sector should get adequate support for the high cost of investment in SCM. Agencies such as National Bank for Agriculture And Rural Development (NABARD) and Indian Renewable Energy Development Agency Ltd (IREDA) can be roped in to offer loans and insurance for entities involved in SCM. Punjab Energy Development Agency (PEDA), in partnership with private entities, should also implement pilot programmes to scale up participation in SCM.

- **Boost demand for biomass**

  Participation of the private sector on a larger scale in ex-situ supply chain operations of crop residue is the need of the hour. The Central Electricity Authority of India (CEA) recommends a blend of 5–10 per cent of biomass pellets along with coal in fluidised bed and pulverised coal units. Mandating a similar blending ratio and technical guidelines for residue usage in other industries would create significant demand for crop residue.

- **Regulate prices of crop residue and its products**

  In December 2018, National Thermal Power Corporation (NTPC) invited expression of interest (EOI) for supplying non-torrefied biomass-based pellets for 21 power plants, none



The Punjab State Electricity Regulatory Commission (PSERC) should work with PEDA to establish price regulation for biomass-based products of which are in Punjab (NTPC Limited 2018). In our analysis, the delivery of pellets over a distance of 200 km costs INR 5,500 per tonne. Delivering biomass from Punjab to these NTPC plants would push up the delivered cost of biomass pellets even higher, making it unprofitable for SCM entities to enter into a long-term fuel supply agreement with those power plants. Every year, the Chhattisgarh State Electricity Regulatory Commission (CSERC) fixes the minimum support price for rice husk, which is one of the largest biomasses produced in the state. Unprofitability of supplying residue is one of the reasons SCM entities are not willing to enter into a long-term fuel supply agreement with power plants. Similarly, the Punjab State Electricity Regulatory Commission (PSERC) should work with PEDA to establish price regulation for biomass-based products, making adequate allowance for compensating farmers for costs incurred in managing the waste.

- **Map end-users**

  From the analysis, it is evident that the delivered cost rises with an increase in distance and is very high for a longer distance between the farm and the end-user. If a provision for decentralised sourcing of crop residue within a radius of 5–10 km exists for the end-user, interim storage is not needed and transportation cost comes down significantly. We recommend that the Punjab Energy Development Agency (PEDA) create a database of end-users mapped to their annual crop residue demand. This database would help the SCM entities to optimally plan for storage and logistics. In addition, the areas where there is a deficit in demand or potential end-users the state government can focus their in-situ management resources in that particular areas. As with increase in distance ex-situ becomes less economical and the policymakers should prioritize deployment of in-situ farm implements like Happy seeders in these locations.

Punjab Energy Development Agency (PEDA) needs to create a database of end-users mapped to their annual crop residue demand

- **Create a digital platform to trade crop residue**

  A digital platform, similar to National Agriculture Market (eNAM), connecting farmers, straw banks, end-users, and various stakeholders involved would go a long way in streamlining the supply chain of crop residue. The digital platform should facilitate farmers to raise a request to collect crop residue, and the nearest straw bank could collect the residue from the farm within the stipulated time. For streamlining demand, we recommend that the database mapping individual annual biomass demand to each end-user can be fed into the platform. This would allow the SCM entities to arrange for decentralised sourcing which condense the interim storage and transportation charge significantly.

1. Motivation for the study

Air pollution was the fourth leading risk for premature death globally and responsible for 12.5 per cent of the total deaths in India in 2017 (India State-Level Disease Burden Initiative Air Pollution Collaborators 2020). More than three-fourths of Indians were exposed to particulate matter (PM)$^{2.5}$ levels exceeding National Ambient Air Quality Standards (NAAQS) in 2017 (India State-Level Disease Burden Initiative Air Pollution Collaborators 2020). Several factors contribute to air pollution in the country such as emissions from vehicles, industries, and thermal power plants, agricultural residue and waste burning, construction dust, and use of cheap fuels in the households (Bernard and Kazim 2018).

Stubble burning on farm fields, a common practice in the north-western states of India, is one of the prime contributors to the build-up of aerosols in the Indo-Gangetic plains (Jethva et al. 2019). Residents living in areas around intense stubble burning were found to have a three-fold higher risk of developing an acute respiratory infection (Chakrabarti et al. 2019). The System of Air Quality and Weather Forecasting And Research (SAFAR) under the Ministry of Earth Sciences (MoES) estimates that stubble burning in Punjab and Haryana contributes 40–45 per cent to Delhi's air pollution during peak burning days (Press Trust of India 2019).

Every year, paddy is sown in 31 lakh hectares in Punjab, which generates 20 million tonnes of paddy residue. In 2018, 13 million tonnes (65 per cent of the generated residue) of crop residue were set on fire in the fields of Punjab, which caused a worsening of air quality in the Indo-Gangetic plains (Ministry of Agriculture & Farmers Welfare 2018).

Farmers are forced to burn crop residue in the north-western states of India as massive amount of paddy comes under cultivation and cropping cycle is shortened to less than 20 days (Gupta 2019; Kurinji 2019). The reduced cropping cycle is an offshoot of the *Punjab Preservation of Subsoil Act (2009)*, implemented to conserve groundwater by mandatorily delaying the transplanting of paddy to beyond 10 June (Jain 2019). Before the Act was conceived, farmers cultivated/sowed paddy during April–May every year. A majority of the farmers burn stubble after the kharif harvesting period as they have to clear the field for rabi sowing period, which starts just days after the harvest.

The courts have taken a serious note of stubble burning and have directed the central and state governments to initiate suitable measures to clamp down this practice in Punjab, Haryana and Uttar Pradesh. Happy Seeder, a tractor-operated machine developed by Punjab Agricultural University (PAU) in 2002, is one of the commonly recommended solutions for in-situ management[3] of paddy residue (Goyal 2019). In response to this very ticklish issue, in 2018, the central government launched a scheme titled Promotion of Agricultural Mechanization for In-situ Management of Crop Residue in the States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi with an outlay of INR 1,151.80 crore (INR 591.65 crore for 2018–19 and INR 560.15 crore for 2019–20) (Ministry of Agriculture & Farmers Welfare 2018). The major thrust of this scheme is to provide subsidies for the purchase of several farm equipment, such as Happy Seeders, to ensure adoption of such equipment for crop residue management across Punjab, Haryana and (western) Uttar Pradesh.

It was estimated that Punjab would require 35,000 Happy Seeders to manage the 31 lakh hectares of land under paddy cultivation in 2019

It was estimated that Punjab would require 35,000 Happy Seeders to manage the 31 lakh hectares of land under paddy cultivation in 2019 (N. Gupta 2019). But only 13,700 Happy Seeders were deployed in the state in 2019 (Nirmal 2019; Bhattacharya 2018), well short of the estimated requirement. Surveys indicated that Happy Seeders can save farmers about INR 1,000 per hectare on average as opposed to using conventional methods (Gupta and Somanathan 2016; Gupta 2019). Despite the benefits and government subsidies, farmers state high upfront cost needed to purchase the Happy Seeder[4] and limited role of the implement for just 20 days and idle for the rest of the year as a hindrance for the limited uptake of in-situ methods (A. Kumar 2019). Apprehensions about the yields of wheat and input costs, difficulty in operating the equipment under excess soil moisture due to monsoon rains, and possibility of pest attack further result in poor acceptance of the Happy Seeder by farmers (Kurinji 2019; Chaba 2020a).

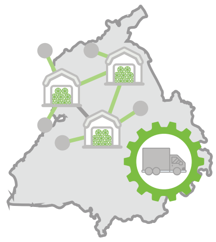
Ploughing back farm waste in situ yields many benefits such as enhancing soil health and improving water retention capacity. But the sheer scale of the residue generated makes it impossible to plough back all of it back into the soil (CII and NITI Aayog 2018). Globally, removing excess residue and using as feedstock for energy purposes proved to increase farmer income (Suardi et al. 2019) . Various existing and emerging technologies such as pyrolysis (biochar), bio-methanation (biogas), and conversion to biofuels (such as briquettes,

3. In-situ management of crop residue involves managing residue in the same field where it gets generated through process such as mulching and incorporation.

4. The average maximum price of a Happy Seeder is INR 1,51,200. The average maximum permissible subsidy per Happy Seeder per beneficiary is INR 75,600, which is 50 per cent of the total cost (Ministry of Agriculture & Farmers Welfare 2018).

pellets, bio-compressed natural gas [CNG], and bio-diesel) have been recommended for ex-situ use of paddy crop residue (CII and NITI Aayog 2018). The National Thermal Power Corporation Limited (NTPC) has demonstrated the use of crop residue in power generation by co-firing seven per cent blend of biomass pellets with coal in Dadri Power Plant, Uttar Pradesh (Central Electricity Authority 2017). However, lack of an assured supply of biomass in adequate quantities proves to be a dampener for private firms to set up biomass plants as they find it economically unviable to invest INR 4.45 to 6 crore per MW (Central Electricity Regulatory Commission 2019).

Given the voluminous nature and seasonal availability of the crop residue, its handling and on-time delivery become a central issue, as it requires a vast workforce, heavy vehicles for logistics and extensive storage infrastructure. The consumption of 13 million tonnes (that was burnt in 2018) of crop residue and a reliable supply of biomass to the end-user requires a dense network of collection centres and supply chain management (SCM) facilities in Punjab. But the high cost of collection and transportation of residue from the field to end-user proves to be the prime impediment for scaling up its ex-situ management (J. Singh, Panesar, and Sharma 2010).



A reliable supply of biomass to the end-user requires a dense network of collection centres and supply chain management (SCM) facilities in Punjab

We carried out this study to improve the current understanding of the economics involved in the supply of biomass to end-user in Punjab. In the course of our work, we have gathered insights on the delivered cost of various types of biomass products such as bales, briquettes, and pellets to the end-users. We further probe the delivered cost of crop residue or its derivatives, which can be used as a supplement to coal in power generation.

Farmers use balers to densify biomass into bales for better handling and smoother transportation.

Image: A2P Energy

2. Status of crop residue management in Punjab

In 2018, about 31.03 lakh hectares of land in Punjab was under paddy cultivation, producing 13 million tonnes of rice as well as generating 20 million tonnes of paddy straw (Government of Punjab 2019). Districts such as Amritsar, Bhatinda, Ferozepur, Ludhiana, Moga, Patiala, and Tarn Taran generated more than 1 million tonnes of residue (Figure 1).

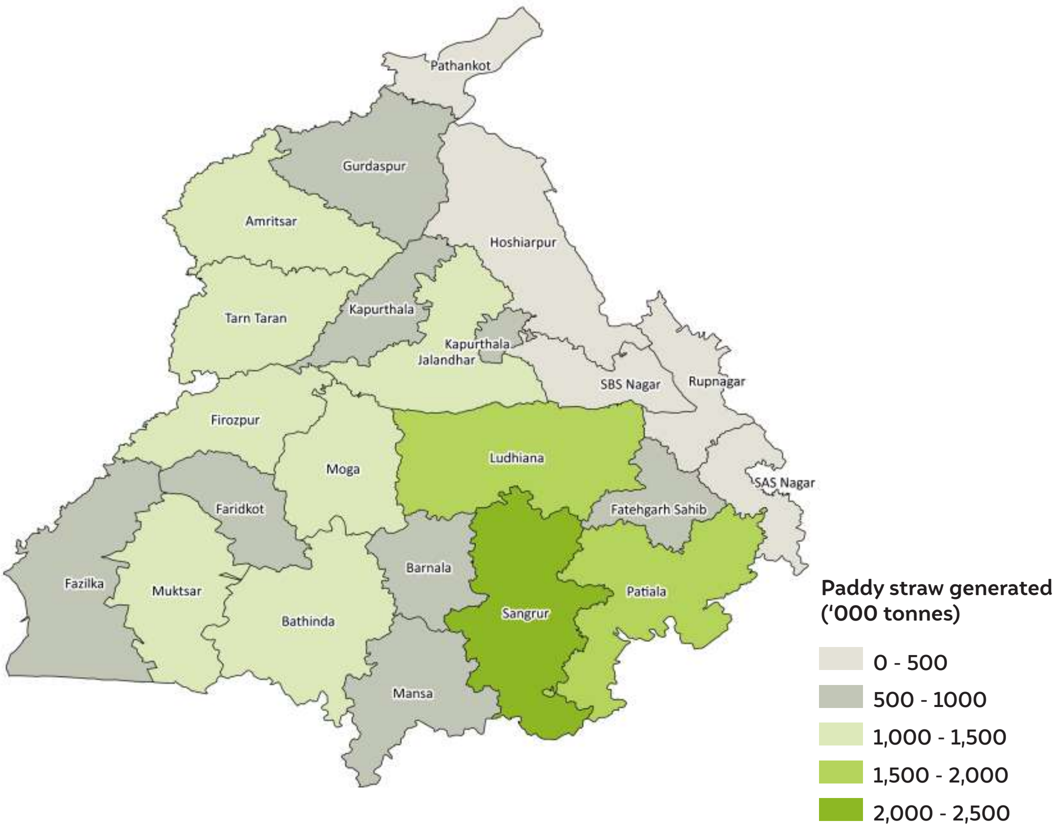


Figure 1
Ludhiana and Sangrur districts generate the highest amount of paddy residue in Punjab (2019)

Source: Authors' compilation

The government's review report claims that 3.52 million tonnes of residue were managed using in-situ methods in the state in 2018 (Ministry of Agriculture & Farmers Welfare 2018). But about 13 million tonnes were burnt on the field in 2018, as a result of which 55,000 incidents of fire were recorded (Kurinji 2019). About 2.7 million tonnes of paddy residue produced in 5 lakh hectares of basmati cultivation was utilised as animal fodder (Ministry of Agriculture & Farmers Welfare 2018). Information gathered from prominent stakeholders involved in ex-situ management shows that 1.1 million tonnes of paddy residue (Ministry of Agriculture & Farmers Welfare 2018) were utilised for ex-situ applications such as in biomass power plants and paper and cardboard industries. Table 1 provides a list of few prominent companies involved in the SCM of crop residue in Punjab, some of which are in construction stage.

As of 2020, Punjab has 11 biomass power plants, with an aggregate capacity of 97.50 MW, consuming 8.80 lakh million tonnes of paddy residue annually. Two more biomass power projects with 14 MW capacity (consuming 1.26 lakh metric tonnes per annum) are slated to be commissioned in June 2021. Other than biomass projects, eight bio-CNG projects are being executed in the state. These can use around 3 lakh metric tonnes of paddy residue annually. A bio-ethanol plant located in Bhatinda with a capacity of 100 kilolitres per day, which is under execution, will utilise 2 lakh metric tonnes of paddy stubble annually. When all these projects are commissioned, 1.5 million tonnes of paddy residue would be consumed by them annually ex-situ, which constitutes 7 per cent of the total residue generated in the state (Chaba 2020b).

Table 1
A few prominent ex-situ management companies in Punjab

Company	Products	Residue managed
Agri2Power (A2P) and Energy Harvest, Chandigarh	- Biomass supply chain management - Pellet	2,450 tonne/annum
Punjab State Council on Science and Technology (PSCST), Chandigarh	- Briquettes	4,000 tonne/annum
Punjab Renewable Energy Systems Pvt. Ltd. (PRESPL)	- Pellets - Briquettes - Biomass supply chain management	62,500 tonne/annum
Neway Renewable Energy Bathinda Private Limited (NREBPL), Mohali	- Bio coal	7,35,000 tonne/annum
CH4 Biotech, Fazilka, Punjab	- Biogas	9,800 tonne/annum
Bioendev AB, Mohali, Punjab	- Torrified biomass pellets	700 tonnes/annum
Farm2energy, Bija, Punjab	- Biomass supply chain management - Bio coal	61,250 tonne/annum
RY Energies	- Biomass supply chain management	1,500 tonne/annum
Sukhbir Agro Energy Ltd	- Biomass energy generation	5,80,000 tonne/annum
Verbio India Pvt Ltd*	- Bio-CNG - Organic manure	90,000 tonne/annum

Source: Authors' compilation

Note: Plant in the development stage

3. Approach and methodology

We estimate the cost incurred in each stage of biomass supply to study the economics of mobilising paddy crop residue for energy conversion. We collected primary data through direct interaction with prominent stakeholders involved in crop residue supply chain management (SCM) in Punjab. Besides primary data from stakeholders, we also used the secondary data from various sources such as government reports, newspaper articles, official government websites, and peer-reviewed journals to estimate the cost involved in the processing of crop residue.

3.1 Cost computation

The supply chain of crop residue involves several steps such as residue collection from the field, first-mile transportation to collection centre/straw bank, interim storage at the straw bank, processing of biomass, and final transportation to the end-user. These steps are illustrated in Table 2.

Table 2 Supply chain of crop residue for ex-situ management

Residue collection	First-mile transportation	Interim storage (Optional)	Biomass processing (Optional)	Last-mile transportation
Paddy residue is chopped off from the field, collected, and densified into bales for smooth transportation.	The bales are loaded in a low-bed trolley/trailer and delivered to the nearest straw bank.	The bales are unloaded and stacked at the straw bank. This stage is optional as biomass can directly be supplied to end-user, which would eliminate storage cost and other costs associated with it.	These bales are further densified into briquettes or pellets based on end-users' requirement.	The bales or processed briquettes/pel-lets are dispatched to the end-user in a truck.
Farm to straw bank		Straw bank to end-user		

Source: Authors' compilation

To calculate the delivered cost of biomass for the end-user, we divided the supply chain into two parts: farm to straw bank and straw bank to end-user (Table 3).

Farm to straw bank

For computing expenses incurred for residue transportation from farm to the straw bank, we consider the rental cost of machinery (such as chopper/cutter-cum-spreader, baler, and raker), labour, and fuel required for cutting and baling of paddy residue, loading and unloading cost of bales at farm and straw bank, and transportation charges for carrying bales from farm to straw bank (Table 3). Our discussion with stakeholders indicates that the collection radius of bales should not exceed 15 km from the straw bank (optimum distance) as the transport charges become uneconomical beyond 15km. Hence, we consider the average cost of sourcing bales from the farm to the straw bank in the 5–15 km radius for the final delivered cost of biomass from straw bank to the end-user.

Straw bank to end-user

For costs incurred to transport farm residue from straw bank to end-user, we consider biomass conversion cost (briquetting and pelleting cost), loading and unloading cost at the straw bank and end-user, respectively, and transportation charges. Truck rental charges include the labour and fuel charge, and it varies with the distance travelled (Table 3). Annexure A1 provides the details on the data used and their source.

Table 3
Data considered for computing cost to transport crop residue from farm to end-user

<table>
<tr><th>Fragments</th><th>Steps involved</th><th>Farm implements/ facilities needed</th><th>Truck</th></tr>
<tr><td rowspan="3">Farm to straw bank</td><td rowspan="2">Residue collection</td><td>Chopper cum spreader</td><td>Rental cost: INR 1,000–1,200/8 hours in a day
Field capacity: 3–4 acre/hour</td></tr>
<tr><td>Raker + baler</td><td>Rental cost: INR 1,500–2,000/acre (rental cost includes fuel and labour)</td></tr>
<tr><td>First-mile transportation</td><td>Tractor-trailer</td><td>Rental cost: INR 245/hour</td></tr>
<tr><td rowspan="4">Straw bank to end-user</td><td rowspan="2">Interim storage (optional)</td><td>Unloading machinery (optional)</td><td>Rental cost: INR 750–800/hour</td></tr>
<tr><td>Storage Cost</td><td>Total capital and operational cost: INR 880/tonne</td></tr>
<tr><td>Biomass processing (optional)</td><td>Cutter and grinder
Briquette/pellet press</td><td>Total operational cost: INR 587/tonne
Total operational cost:
INR 418/tonne (briquette)
INR 818/tonne (pellet)</td></tr>
<tr><td>Final transportation</td><td>Truck</td><td>Transport cost (Includes fuel cost and driver charges) (INR/km):
Transport cost (0–50 km) 40
Transport cost (51–150 km) 39
Transport cost (151–300 km) 38
Transport cost (301–500 km) 37
Transport cost (501–1,000 km) 36</td></tr>
</table>

Source: Authors' compilation; Based on the discussion with prominent ex-situ crop residue management entities in Punjab; (M. Sharma et al. 2019)

Heavy vehicles for logistics and a vast workforce are needed for handling and on-time delivery of crop residue to end-users.

Image: iStock

4. Results and discussion

In this chapter, we pay attention to metrics involved in the supply chain of residue, including the delivered cost of paddy residue, optimum distance, and form for residue preferred for transit, and the challenges plaguing the adoption of ex-situ option.

4.1 Cost of biomass aggregation from farm to the straw bank

The collection cost of crop residue varies depending on the distance between the straw bank and the farm. A straw bank should be ideally located within 15 km from the farm. Crop residue is generally transported in the form of bales as it makes handling and transportation easier and facilitates safe storage (A. Sharma and Chandel 2016). As per our calculations, the transit of paddy residue in the form of bales over a distance of 5–15 km typically costs INR 1,150-1,330 per tonne (Figure 2). The cost of cutting and baling residue accounts for 55 per cent of the sourcing cost of residue from the farm to a straw bank located at a distance of 15 km (Figure 3). The major component of this processing cost is the rental cost of several farm machinery involved such as chopper, raker, and baler (details shown in Annexure A2).

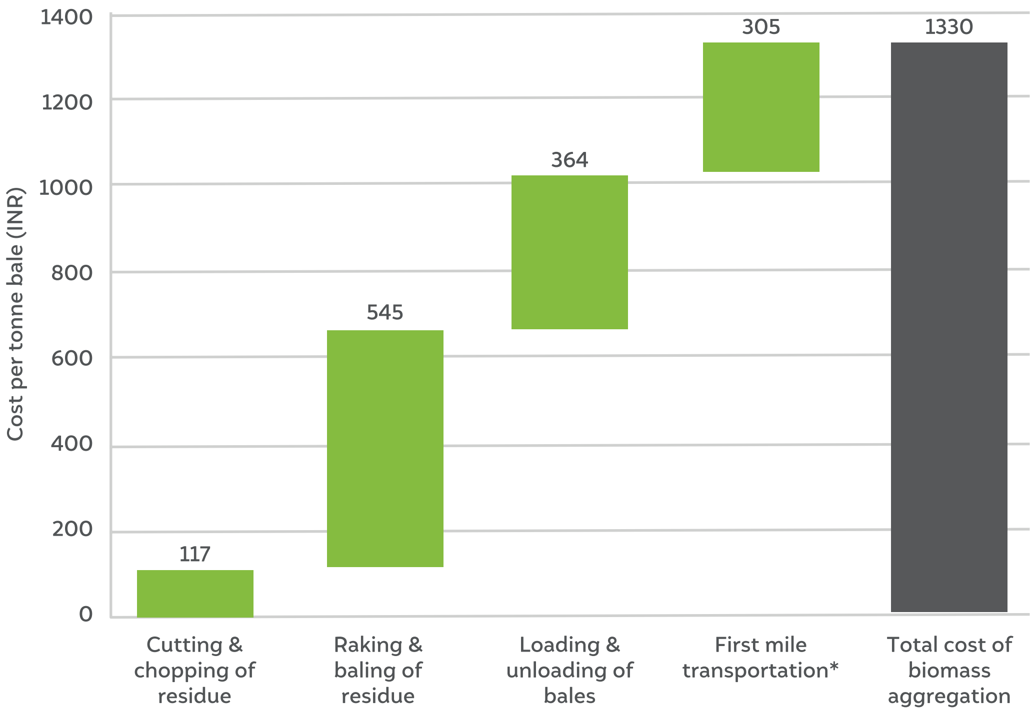


Figure 2
Raking and baling cost is the highest in the transportation of crop residue from farm to the straw bank

Source: Authors' analysis;

*An optimum distance of 15 km between farm and straw bank is considered.

In most cases, supply chain entities provide customised farm implements needed for residue collection, as evidently a majority of individual farmers do not maintain a repository of ex-situ farm implements, as heavy investment is needed for buying them (Confederation of Indian Industry; German Agribusiness Alliance 2020)(Rao 2019; Moudgil 2020). A few entities use 'on-demand' model to locally source the farm implements from custom hiring centres (CHCs) or large farmers and provide those implements 'on-demand' to individual farmers. SCM entities usually bear all the cost incurred in residue collection and transportation of residue.

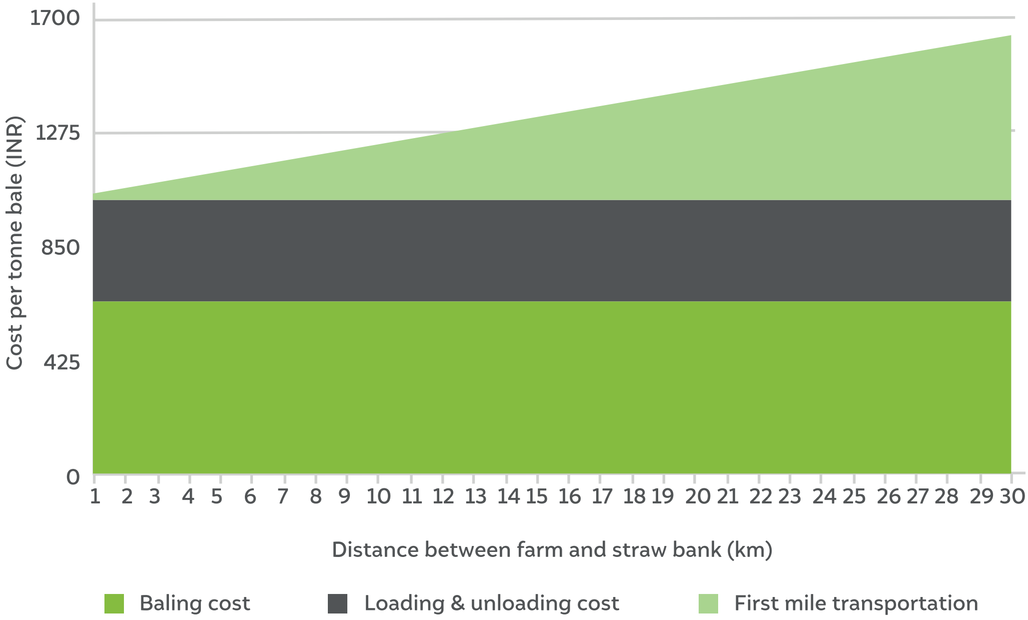


Figure 3
Cutting and baling entail a high cost in the shifting of bale from farm to the straw bank

Source: Authors' analysis

Role of straw banks

Farmers in Punjab have a limited span of 15-20 days available for preparing the land for the next crop. This makes the collection process of paddy residue onerous, as it gives a small window for chopping, balling, and transfer of paddy residue from farm to the straw bank. So interim storage in the form of straw banks/ collection centres allows more time for the processing and transport of residue to the end-user. A straw bank, spanning over an area of 10–15 acres, can hold up to 10,000–15,000 tonnes of residue.[5] This means 850–1,300 straw banks are needed, spread over an area of 13,000 acres (5,260 hectares) in Punjab, for preparing 13 million tonnes[6] of residue for ex-situ applications.

SCM entities usually lease land, typically for three to six months, to set up a straw bank for a rental cost of INR 50,000–1,00,000 per hectare, depending on the type of land. Generally, straw banks should be located on common panchayat land or other fallow lands available, as rental charges would be lower for them compared to farmlands. Straw banks should be equipped with safeguards against fire hazards as stored residue often catches fire due to various factors such as increased ambient temperature, chafing of bales with each other, and human-induced factors, resulting in considerable losses. Maintaining a safe distance between piles may reduce the risks of fire. Further, prolonged storage can also result in loss of

5. Small SCM entities may also set up straw banks spaning over an area of less than 10 acres.

6. We use the example of 13 million tonnes, as it is the amount of paddy residue that was burnt on the farm in 2018.

dry and organic matter, substantial reductions in heating value, and volatile matter (Blunk et al. 2003).

4.2 Delivered cost of residue from farm to end-user

SCM entities generally densify the biomass to increase the bulk and energy density of raw biomass for easy storage and handling and improve transport efficiency and cost (Ray et al. 2017). Baling, briquetting, and pelleting are the methods used to densify biomass based on the end-users' need.[7] To compute the delivered cost of residue from farm to end-user, we take into account three forms of biomass transported to the end-user as shown in Table 4.

Pathway I	Pathway II	Pathway III
Transit of residue in the form of bales from straw bank to end-user	The residue is converted into briquettes in the straw bank and then dispatched to the end-user	The residue is converted into pellets in the straw bank and then dispatched to the end-user
End-users of bales: Biomass power plants, packaging industry, and paper and cardboard industry	End-users of briquettes: Large and medium-scale industrial boilers and other heating requirements	End-users of pellets: coal power plants, smaller devices such as pellet stove and furnace

Table 4
Pathways for different versions of biomass

Source: Authors' analysis

For scenarios II and III, we assume that decentralised briquetting and pelletisation plants are available at the straw bank. We calculate the total operational cost of these plants at INR 1,034 per tonne of briquettes and INR 1,433 per tonne of pellets, respectively. Tables A4 and A5 respectively in the Annexure provide detailed estimates on the economics of briquetting and pelletisation plants. The cost break-up of per tonne of biomass supplied to the end-user located at a distance of 50 km is shown in Table 5.

Biomass pellets occupy a larger contact area with air compared to briquettes. Hence, in well-ventilated conditions, biomass pellets are easier to burn, faster to transfer heat, and burn more sufficiently. But biomass briquettes are superior in terms of burning time. Both briquettes and pellets can be used in boilers and stoves. But considering their different sizes, briquettes are preferred in large and medium-scale boilers, while pellets are widely used in small-sized devices, such as pellet stove, furnace, and cooking range (The AGICO 2020). As briquette and pellets are preferred over bales because of their increased energy content in industries and power plants, we also estimate and compare the delivered cost per 5,000 Mcal of bales with briquettes and pellets.

7. The density of loose paddy straw, collected directly from the field, can range from 13 to 18 kg m^{-3} in dry matter (dm). The density of round paddy straw bale with a length of 70 cm and a diameter of 50 cm range from 60 to 90 kg m^{-3} dm. The density of paddy straw briquettes with a 90-mm diameter and 7- to 15-mm thickness is 350–450 kg m^{-3} dm. The density of rice straw pellets with an 8-mm diameter and from 30 to 50 mm in height is 600–700 kg m^{-3} dm. (Van Hung et al. 2020).

Fragments	Components	Bale (INR)	Briquette* (INR)	Pellet* (INR)
Residue collection + first-mile transportation	Residue cost	1,351	1,757	1,757
Interim storage (optional)	Storage cost	880	1,144	1,144
Biomass processing (optional)	Biomass processing cost (briquette/pellet)	NA	1,034	1,434
Final transportation	Transport charges	347	250	250
	Loading and unloading cost	364	135	135
Total cost (INR/tonne)		**2,942**	**4,319**	**4,720**
Total cost (INR/5,000 Mcal)		**5,979**	**6,012**	**6,626**

Table 5
Delivered cost of biomass to the end-user located at a distance of 50 km

Source: Authors' analysis

*About 1.3 tonne of residue is required to produce 1 tonne of briquette/pellet. Additional cost of collection, transportation and storage of 0.3 tonnes of residue for every tonne of briquette and pellets has been added to briquettes and pellets resulting in the variation of collection, first mile transportation and storage cost between the three forms of biomass.

Scenario I: Transit in the form of bales

The delivered cost of bales for a distance of 50 km between the straw bank and the end-user is INR 2,940 per tonne of bale. Storage charges account for 30 per cent of the total delivered cost per tonne. Transportation charge per tonne is INR 350 for a distance of 50 km between the straw bank and the end-user, which will go up as the distance increases (Figure 4). Conversations with crop residue SCM entities reveal that transport of biomass is profitable up to a distance of 50 km, beyond which it gets expensive. However, in the case of end-users located far away from the farms, the residue can also be dispatched beyond 100 km.

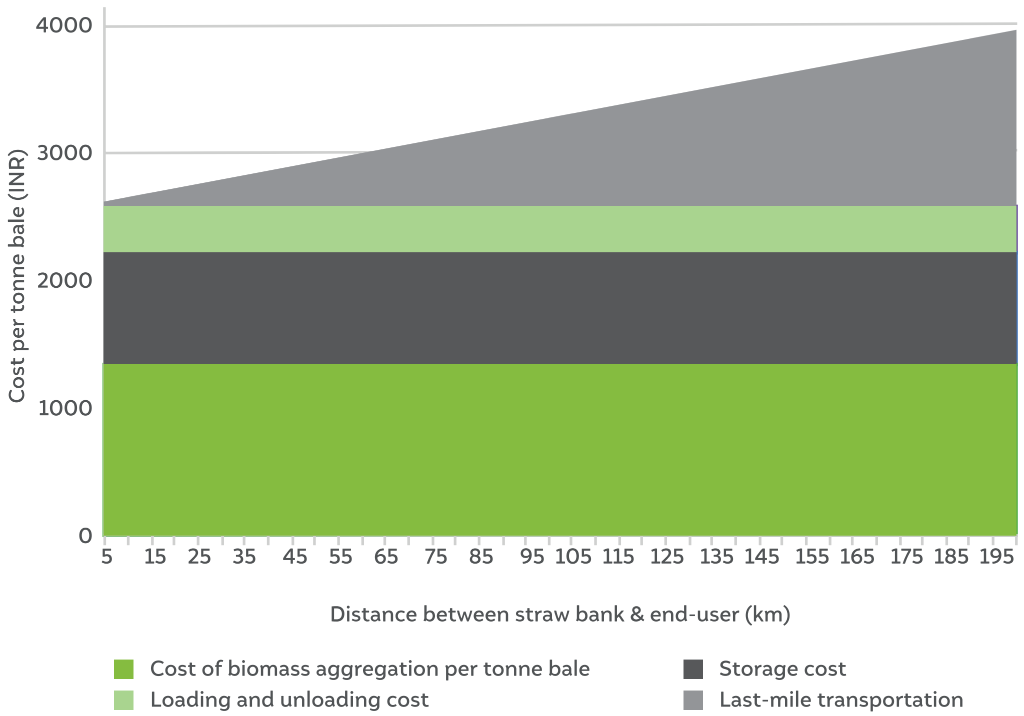


Figure 4
Cost of aggregation of biomass takes the largest slice of the delivered cost of per tonne bale from farm to end-user

Source: Authors' analysis

Scenario II: Transit in the form of briquettes

Several field studies demonstrate that densifying biomass reduces transportation cost by 60 per cent and the required quantity of trucks by 63 per cent (Balingbing et al. 2020; Possidônio et al. 2016). The other benefits are that densifying also increases energy density and significantly reduces handling difficulties (Clarke and Preto 2011). But, in our analysis, the cost paid for the operation of briquette plants largely offsets the cost benefits of the densification process. But the higher processing cost incurred is subsequently passed on to the end-user.

We estimate a delivered cost of INR 4,320 and INR 4,570 per tonne briquettes for a distance of 50 km and 100 km, respectively (Figure 5). For a distance of 150 km, the delivered cost of briquettes is INR 4,820 per tonne, 1.3 times higher than the delivered cost per tonne of bales for the same distance. However, the delivered cost of briquettes per 5,000 Mcal of energy for a distance of 150 is INR 6,340, 4 per cent lower than that of bales.

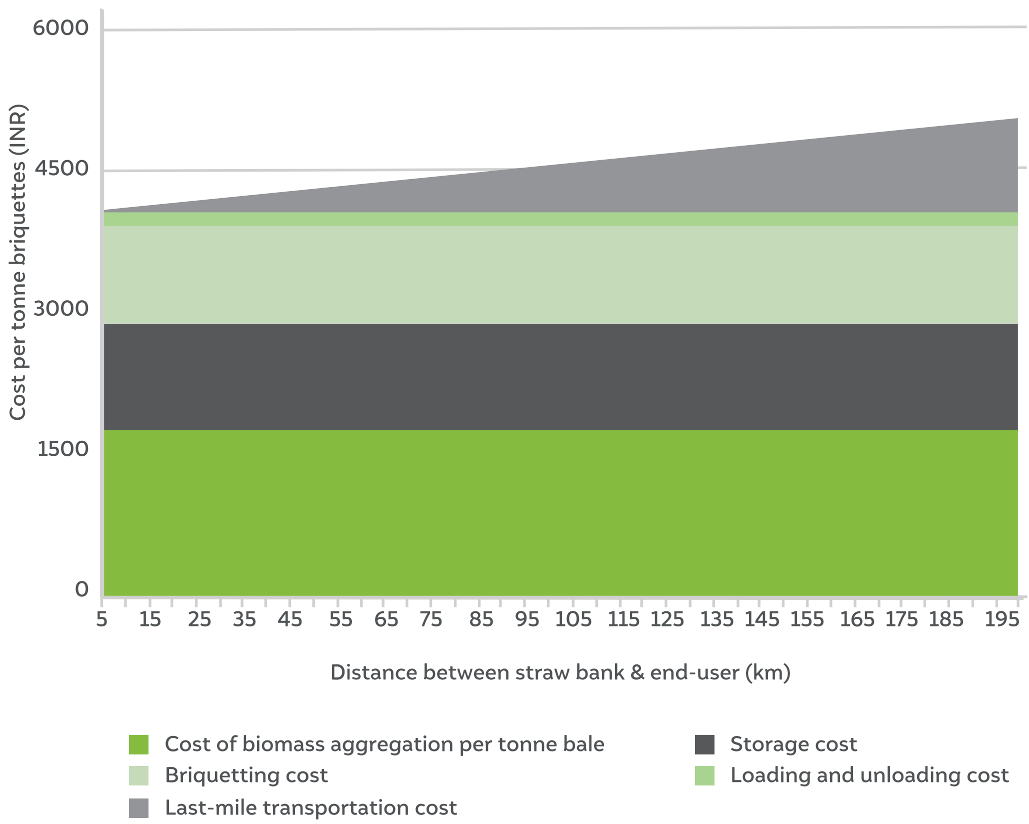


Figure 5 Briquetting cost adds up to significantly to the delivered cost of briquettes from farm to end-user

Source: Authors' analysis

Scenario III: Transit in the form of pellets

Compared with other densification processes, such as baling and briquetting, pelleting makes biomass most durable as the crop residue is subjected to the highest amount of pressure (Whittaker and Shield 2017). Pelletisation can increase the bulk density of the biomass from an initial value of 40–200 kg m^{-3} to a final bulk density of 600–700 kg m^{-3} (Balingbing et al. 2020; Van Hung et al. 2020).

We find a delivered cost of INR 4,720 and INR 4,970 per tonne of pellets for a distance of 50 km and 100 km, respectively (Figure 6). For a distance of 150 km, the delivered cost of pellets is INR 5,220 per tonne, 1.44 times higher than the delivered cost per tonne of bales for the same distance. Further, the delivered cost of pellets per 5,000 Mcal of energy for a distance of 150 km shoots up to INR 7,000, a 5.3 per cent higher cost than bales.

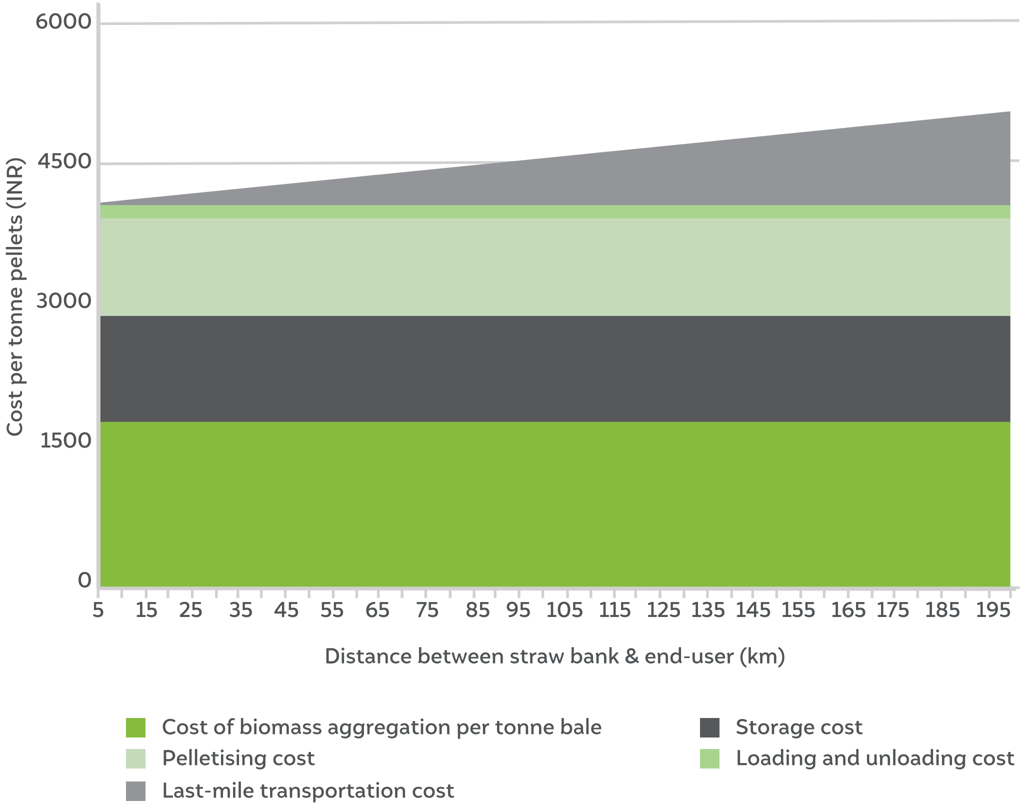


Figure 6
Delivered cost of per tonne of pellets from farm to end-user is highest among all processing options for crop residue

Source: Authors' analysis

Different end-users require biomass in different forms. Industries such as biomass power plants, packaging, and paper and cardboard industries require biomass in the bale form, whereas briquettes are used in large and medium-scale industry boilers as it is conducive to heating. But coal-fired power plants and smaller heating devices such as pellet stove and furnace prefer the pellet form of the biomass. Transporting residue in the form of pellets entails the highest cost compared to bales or briquettes owing to the high processing cost involved (Figure 7). In most cases, SCM entities transport residue in the form of bales to avoid the high investment needed for biomass processing. In such instances, the end-user has to invest in processing bales to briquettes or biomass if required.

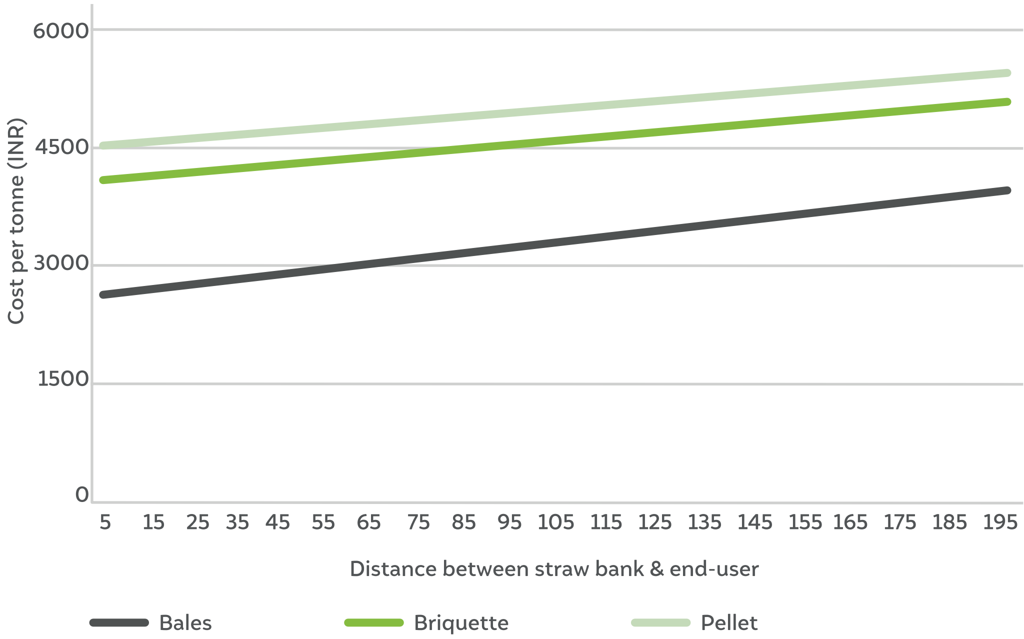


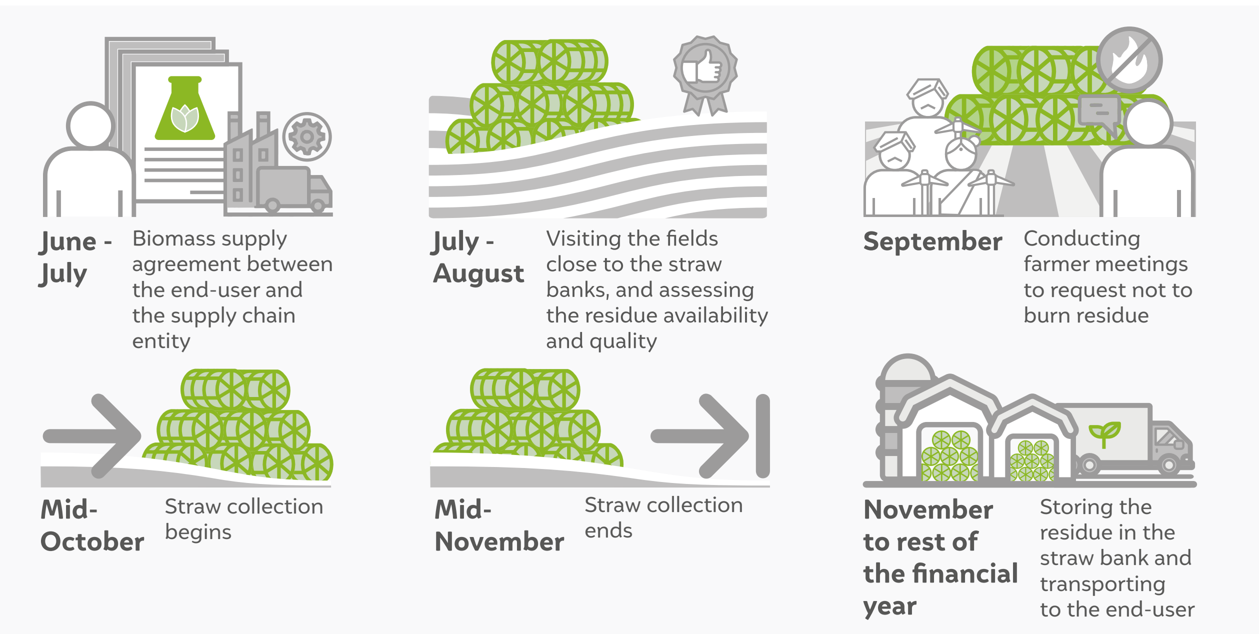
Figure 7
Delivered cost of biomass-based products increases with distance

Source: Authors' analysis

Mapping the end-users

The entire process of supplying crop residue for ex-situ uses takes between 6 and 12 months (Table 6). The delivered cost rises with an increase in distance and is very high for a longer distance between the farm and the end-user (Figure 7). If a provision for decentralised sourcing of crop residue within a radius of 5–10 km exists for the end-user, interim storage is not needed and transportation cost comes down significantly. We recommend that the Punjab Energy Development Agency (PEDA) create a database of end-users mapped to their annual crop residue demand. This database would help the SCM entities to optimally plan for storage and logistics. In addition, the areas where there is a deficit in demand or potential end-users the state government can focus their in-situ management resources in that particular areas. In those regions, more CHCs need to be strategically established to increase the accessibility of in-situ farm implements such as Happy seeder.

Table 6 Timeline of an ex-situ crop residue operation



Source: Authors' compilation based on the discussion with prominent ex-situ entities in Punjab

Co-firing biomass in thermal power plants

Several countries see co-firing biomass with coal for electricity generation and other heating requirements in power plants and industries as an attractive option because of the derived social and environmental benefits (Demirbas 2003; Hansson et al. 2009; Sullivan and Meijer 2010). The limitations of this application of biomass include low heating values, variable chemical and physical properties, high investment and operating cost, and unreliable biomass feedstock supply (Dai et al. 2008).

Coal-fired thermal power plants contribute 58.26 per cent to the total installed capacity of 14,205.42 MW in Punjab (Central Electricity Authority 2020). The two thermal power plants operating on coal (Punjab State Power Corporation Limited 2020) in Punjab require 11.34 million tonnes of coal per annum (Government of India and Government of Punjab 2016).

Power demand in Punjab generally peaks during the kharif season mainly for irrigation needs. In early 2020, due to the COVID-19 pandemic-induced lockdown, energy demand dropped as most industries were not functioning in the state. By procuring cheaper coal from Coal India Limited (CIL) rather than relying upon coal imports (Tribune News 2020), Punjab State Power Corporation Limited (PSPCL) intends to save INR 100 crore for the Punjab government. But the use of cheaper coal is not conducive to the environment due to increased NOx emissions (Agraniotis et al. 2017). One possible option to reduce coal consumption is to co-fire thermal plants with 10 per cent of biomass, which offers twin benefits of reduced pollution and consumption of crop waste. For instance, if 10 per cent of paddy residue pellets are blended with coal, it would lead to a consumption of 1.47 million tonnes of paddy residue annually. We recommend that the Punjab government actively look at the option of co-firing coal-fired power plants with biomass. We also offer the same recommendation to states such as Haryana and Uttar Pradesh that resort to stubble burning on a large scale.

Industries that consume coal for their heating needs should explore the prospects of locally sourcing the biomass briquettes within the state

We now see how the economics of biomass as feedstock supply works out against coal. We take the delivered price of coal from the tariff order of Guru Gobind Singh Super Thermal Power Plant, Ropar, Punjab, for the financial year 2018–19 for our comparison. We note that the delivered cost of biomass pellets per 5,000 Mcal within a radius of 50 km of the power plant is economical compared to coal (Figure 8). On the other hand, the delivered cost of briquettes per 5,000 Mcal is economical up to a distance of 145 km. Therefore, we recommend that industries that consume coal for its heating needs should explore the prospects of locally sourcing the biomass briquettes within the state.

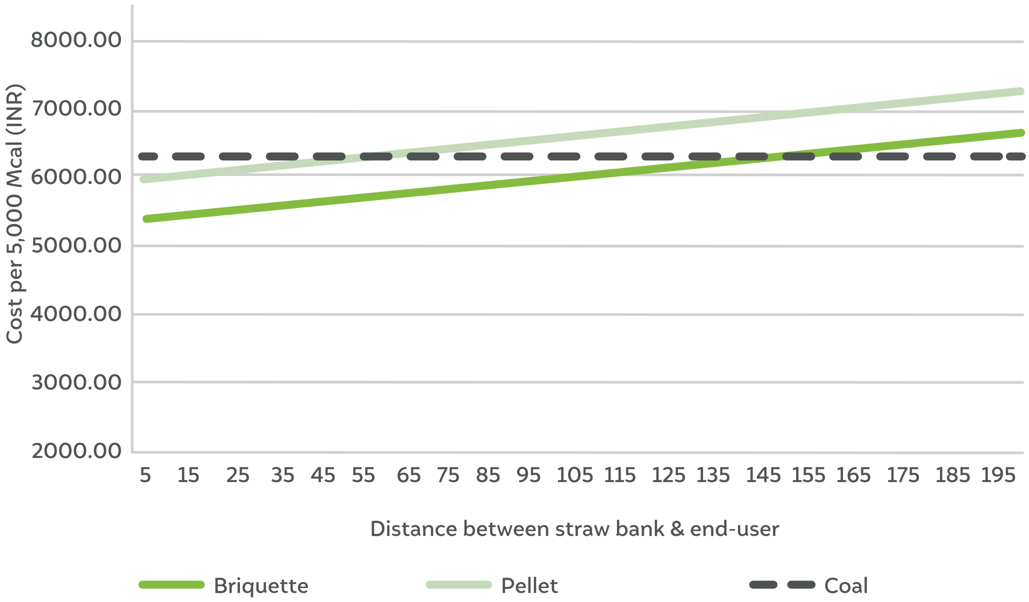


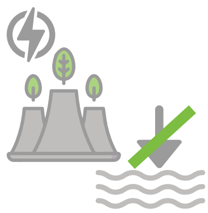
Figure 8
Delivered cost of briquetted and pelleted biomass is lower than that of coal up to a certain distance between the farm and the end-user

Source: Authors' analysis

4.3 Concerns regarding the use of paddy residue for ex-situ applications

The Punjab government reported that 12.85 million tonnes of paddy were burnt in the state in 2018 (Ministry of Agriculture & Farmers Welfare 2018). For collecting all of this paddy straw, transporting, and storing them at straw banks, 37,000 tractor-trailers would be needed every day on the village roads of Punjab for 20 days during the kharif harvesting season. This is not viable as village roads may get congested when handling a high volume of traffic due to poor infrastructure.[8] Also, residue collection at this scale is estimated to lead to an emission of 29 Gg CO_2.[9] A detailed assessment of traffic congestion on village roads and vehicular emissions involved in logistics of a huge scale of biomass use is needed. Further, a rigorous life-cycle assessment (LCA) of SCM would help project managers in deciding the ideal fuel for logistics and biomass processing.

During the harvesting season in Punjab, the high dew content leaves a larger moisture content in paddy residue. The residue is generally sun-dried to bring down the moisture content to 10 per cent. If moisture content doesn't drop to 10 per cent or below, drying equipment should be used, which entails additional expenditure. SCM entities also need to find a way to optimise logistics cost as trucks return empty to the farm after delivering biomass to straw banks.



Setting up new biomass plants for power generation would strain the state's already depleting water reserves

Thermal power plants need water in the range of 3.5–9 m^3/hour per MW depending upon the technology deployed for power generation (Chaturvedi et al. 2018). Comparatively, an 18 MW biomass power plant in Punjab needs 225 m^3/hour of water (Joshi et al. 2019). Punjab has 11 operational biomass power plants with an aggregate capacity of 92.60 MW. These plants consume 8.80 lakh tonnes of paddy straw, which is 2.75 per cent of the total paddy residue generated in Punjab annually. The Punjab government is also planning to set up several new biomass-based refineries and power plants in the state to tackle the problem of stubble

8. To collect 13 million tonne of paddy residue, 37,143 tractor-trailer trips would be required for 20 days (assuming 7 tonnes of paddy residue is collected in each trip and round trips made by a tractor in one day).

9. Assuming an average distance of 15 km between farm and straw bank, the emission factor for tractor-trailer = 515.2 g CO_2/km (Ramachandra and Shwetmala 2009).

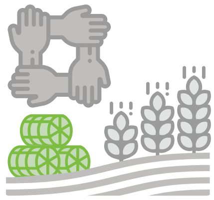
burning (Chaba 2019). A dystopian future for Punjab is predicted due to its depleting water reserves on account of a dominant paddy cultivation system in the state (Tur 2018; Krishan et al. 2014; Baweja et al. 2017). It is also known that out of all power generation technologies, biomass-based projects need a very high amount of water (Zhu, et al. 2019). Setting up new biomass plants for power generation surely would strain the state's already depleting water reserves. Hence, detailed studies are needed to quantify water footprint for setting up and operating new plants and also to determine the source of required water.

5. Policy recommendations

For this study, we interacted with several stakeholders involved in the SCM of crop residue in Punjab. We specifically looked at the ex-situ crop residue management in the state and its economics. Based on our observations and consultations, we recommend the following strategies for better management and scaling up the ex-situ applications of crop residue in Punjab.

5.1 Establish a dense network of straw banks and ex-situ supply chain ecosystem

From our estimates and stakeholder dialogues, ex-situ SCM is found to be financially viable when crop residue collection is done within 15 km and supplied to the end-user situated within 50 km. A dense network of straw banks and an efficient SCM can help achieve these targets. Also, a huge opportunity for green jobs is also created in the rural areas of Punjab. Interim storage at straw banks approximately cost INR 800 per tonne. Storing 13 million tonnes of paddy residue (burnt in 2018) in the straw banks would cost INR 1,040 crores. Needless to say, this investment needs to be mobilised from the private sector. The Punjab government should make way for SCM entities to lease common panchayat land or other fallow lands as it reduces storage cost. Agencies such as National Bank for Agriculture And Rural Development (NABARD) and Indian Renewable Energy Development Agency Ltd (IREDA) could be roped in to provide loans and insurance for entities involved in SCM. Government agencies such as PEDA in partnership with private entities should also implement pilot programmes to scale up participation of the private sector in ex-situ crop residue management.



Government agencies such as PEDA in partnership with private entities should also implement pilot programmes to scale up participation of the private sector in ex-situ crop residue management.

5.2 Regulation for minimum crop residue usage

Boosting the demand for biomass would encourage participation of the private sector in ex-situ supply chain operations. The Central Electricity Authority of India (CEA) recommends a blend of 5–10 per cent of biomass pellets along with coal in the fluidised bed and pulverised coal units (Central Electricity Authority 2017). If state's coal-fired thermal power plants are co-fired with 10 per cent of blended biomass pellets, it would take up 1.47 million tonnes of paddy residue annually. We also urge the Punjab government to introduce a regulation mandating the minimum usage ratio of crop residue biomass in industrial boilers, coal-fired thermal plants, and biomass electricity generation projects. Stipulating a blending ratio and issue of technical guidelines for residue usage in industries will certainly boost its uptake.

5.3 Price regulation of crop residue and its products

In December 2018, NTPC invited expression of interest (EOI) for supplying non-torrefied biomass-based pellets for 21 power plants, none of which are in Punjab (NTPC Limited 2018). We arrived at a delivered cost of biomass at INR 5,500 for a distance of 200 km. Delivering biomass from Punjab to these NTPC plants would push up the delivered cost of biomass pellets even higher, making it unprofitable for SCM entities to enter into a long-term fuel supply agreement with those power plants. Every year, the Chhattisgarh State Electricity Regulatory Commission (CSERC) fixes the minimum support price for rice husk, which is one of the largest biomasses produced in the state. We also suggest to PSERC (along with PEDA) to establish a minimum price for biomass-based products every year by making an allowance for adequate compensation to farmers for the costs they incur in getting the crop residue out of their farm. This would also reduce the monopoly of SCM entities over prices and provide them with satisfactory profit and also reasonable prices for end-users.

5.4 Mapping of end-users

The entire process of supplying crop residue for ex-situ uses takes between 6 and 12 months. From the analysis, it is evident that the delivered cost rises with an increase in distance and is very high for a longer distance between the farm and the end-user. If a provision for decentralised sourcing of crop residue within a radius of 5–10 km exists for the end-user, interim storage is not needed and transportation cost comes down significantly. We recommend that the PEDA create a database of end-users mapped to their annual crop residue demand. This database would help the SCM entities to optimally plan for storage and logistics. In addition, the areas where there is a deficit in demand or potential end-users the state government can focus their in-situ management resources in that particular areas. As with increase in distance ex-situ becomes less economical, the policymakers should prioritize deployment of in-situ farm implements like Happy seeders in these locations.

If a provision for decentralised sourcing of crop residue within a radius of 5–10 km exists for the end-user, interim storage is not needed and transportation cost comes down significantly.

5.5 Digital platform for farmers to trade their residue

For an efficient supply chain management, a digital platform, similar to National Agriculture Market (eNAM), connecting farmers, straw banks, end-users, and various stakeholders needs to be created. We also suggest a process for the functioning of this platform. Farmers should be able to raise a request to collect crop residue from their farm through the platform. The nearest straw bank (ideally within 15 km) would accept the request and collect the residue from the farm within the stipulated time frame. The compensation for the crop residue could be deposited to the farmers' bank account directly. This would ease the burden of farmers in collecting and transporting the residue from their farms to straw banks and increase the profitability of both farmers and straw banks. Also, if a provision exists for end-users to raise a demand request for biomass, SCM entities should be able to arrange for residue collection within a radius of 5–10 km of the end-user. This improves the optimisation of SCM and reduces transport and storage cost.

After harvesting paddy, farmers in Punjab have a limited span of 15-20 days to prepare the land for the next crop. This reduced timeframe is an offshoot of the *Punjab Preservation of Subsoil Act (2009)*, implemented to save groundwater by mandatorily postponing the transplanting of paddy from April–May to beyond 10 June.

Image: iStock

6. Conclusion

Punjab has been experiencing the problem of stubble burning for several decades, causing extensive air pollution. Needless to say, a multi-pronged strategy is needed to curb the practice. Several approaches, including in-situ treatments such as the use of Happy Seeder, mulching, composting, and ex-situ options, have been recommended to dispose of crop residue beneficially. The farmer's choice of crop residue management depends upon the economics of the selected option, availability of implements, and the time needed for its implementation. Burning the stubble on the open field is always the easiest option for farmers. In 2018, 13 million tonnes of paddy residue (65 per cent of the total 20 million tonnes generated) were set on fire in the fields of Punjab, choking the Indo-Gangetic plains. Several experts have expressed the view that biomass-based power generation in Punjab can result in a useful consumption of crop residue as well as reduce pollution from coal-fired thermal power plants. Lack of a dense network of biomass supply chain facilities is proving to be a hurdle for scaling up ex-situ management of crop waste in the state.

Supply chain entities play a prominent role in reaching the biomass from the farmer and the end-user. Only 10 well-known SCM entities are currently involved in the supply chain business in Punjab. Developing a dense network of crop residue managing facilities could significantly reduce cost of transport. Our estimates show that transit of paddy residue in the form of bales for a distance of 5–15 km from farm to straw bank typically costs INR 1,150–1,350 per tonne. Cutting and baling of residue constitutes 55 per cent of the delivered cost of residue from farm to the straw bank. The role of supply chain entities role in providing customised farm implements needed for residue collection assumes greater importance, as individual farmers do not maintain an inventory of ex-situ farm implements.

If the state government decides to use 10 per cent of blended biomass pellets for co-firing state's coal-fired thermal power plants, 1.47 million tonnes of paddy residue will be consumed annually in this process. Introducing a regulation mandating the minimum usage ratio of biomass derived from crop residue and stipulating a blending ratio and technical guidelines for residue usage in appropriate industries will significantly boost the demand for crop residue.

Though biomass pellets are the most demanded form of paddy residue in power plants, our estimates indicate that the delivered cost of pelleted crop residue is the highest among available options. Decentralising the sourcing of crop residue within a radius of 5–10 km of the end-user's location would curtail the need for interim storage and drastically bring down transportation costs. Further, a clear data that maps all the end-users with their annual biomass demand would help supply chain entities to develop clear storage and logistics plans. In addition, the areas where there is a deficit in demand or potential end-users the state government can focus their in-situ management resources in that particular areas. As with increase in distance ex-situ becomes less economical, the policymakers should prioritize deployment of in-situ farm implements like Happy seeders in these locations.

As with increase in distance ex-situ becomes less economical, the policymakers should prioritize deployment of in-situ farm implements like Happy seeders in these locations

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Annexure I

Table A1: Data used to compute the delivered cost of biomass

Parameter	Data	Source
Farm to straw bank		
Diesel price	INR 72.21	Diesel prices for the state of Punjab w.e.f. 10-07-2020 (The Economic Times 2020)
Rice yield of Punjab	4132 kg/ha	Statistical Abstract of Punjab, 2019 (Government of Punjab 2019)
Tractor rent charges	INR 217.14/hour	S. Singh (2018)
Trailer rent charges	INR 27.92/hour	S. Singh (2018)
Working hours of skilled labour required for loading, unloading and stacking	3.4 hour/tonne	Gill, Dogra, and Dogra (2018)
Trailer capacity	7 tonnes	Stakeholder consultation
Straw bank to end-user		
Storage cost	INR 0.80 per kg	Stakeholder consultation
The payload capacity of the truck	8,000 kg	Specifications provided by truck rental service
Truck rental cost per km	INR 40	Per km rate obtained from private truck rental service (includes fuel and other logistic charges) Can vary according to diesel prices and border toll charges (N. Kumar 2020)
Minimum wage (skilled worker)	INR 48.79/hour	Minimum wages for labour for the state of Punjab w.e.f. 01-05-2020 from the Office of The Labour Commissioner, Punjab (Office of the Labour Commissioner 2020)
Energy content of paddy residue	2,750 kcal/kg	NITI Aayog's action Plan for biomass management (CII and NITI Aayog 2018)
Energy content of paddy briquette	3,800 kcal/kg	Technical specification of PRESPL products (Punjab Renewable Energy System Pvt. Ltd 2020)
Energy content of paddy pellet	3,750 kcal/kg	Ishii et al. (2016)

Source: Authors' compilation

Table A2: Data on farm implements involved in cutting and baling the residue

Farm machinery	Fuel (diesel) consumption(litre/acre)	Rental cost (INR/acre)	Note
Chopper/ cutter-cum-spreader	3	157	- Rental cost on time basis: INR 1,000–1,200/ day as charged to farmers by farmer co-op societies - Field capacity: 3–4 acre/hour (15–20 min/ acre)
Baler + Raker	6–7 (Baler) 3–4 (Raker)	1,500–2,000	- Rental cost on acreage basis as charged to farmers by a service provider is INR 1,500–2,000/acre - This rental cost also includes the fuel and labour costs for combine harvester operation - Field capacity: 2 acre/hour (30 min./acre)

Source: (M. Sharma et al. 2019)

Table A3: Freight rates for final transportation

Distance (km)	Transport cost (INR/km)
0 - 50	40
51 - 150	39
151 - 300	38
301 - 500	37
501 - 1000	36

Source: Authors' compilation based on stakeholder consultation
**Note: Cost is relevant for trucks with a payload capacity of 8 tonnes and is subject to change with fluctuation in diesel price*

Table A4: Economics of briquette production

Title	Chaff cutter	Chipper grinder	Briquette press	Operational shed
Depreciation + interest + tax + insurance (INR/hour)	6.26	53.51	66.34	16.62
Electricity required (kWh)	13.51	37.84	53.16	0.96
Electricity cost (INR/hour)	65.80	184.30	258.87	4.65
Labour charges (INR/hour)	104.58	104.58	104.58	
Repair and maintenance (INR/hour)	1.89	16.12	19.98	8.84
Cost of lubrication (INR/hour)	13.16	36.86	51.77	0.93
Miscellaneous cost (INR/hour)	NA	NA	NA	3.54
Total cost (INR/hour)	**191.69**	**395.37**	**501.54**	**34.58**
Total cost (INR/tonne)	**191.69**	**395.37**	**417.95**	**28.82**

Production cost of briquette (INR/tonne)	1,033.83			
Capital cost (principal)	80,000	4,90,000	10,95,000	4,84,376
Average use/yr (hours)	2,120	1,520	2,740	2,740
Salvage value	10% of principal			
Electricity tariff	INR 4.87/kWh			
Interest rate	12%			
Taxes and insurance	1% of principal			
Repair and maintenance	5% of principal			
Miscellaneous cost (INR/hr)	2% of principal			

Source: Authors' analysis; (Gill, Dogra, and Dogra 2018; Punjab State Electricity Regulatory Commission 2019)

Table A5: Economics of pellet production

Title	Chaff cutter	Chipper grinder	Pellet press	Operational shed
Depreciation + interest + tax + insurance (INR/hour)	6.26	53.51	55.33	16.62
Electricity required (kWh)	13.51	37.84	150.00	0.96
Electricity cost (INR/hour)	65.80	184.30	730.50	4.65
Labour charges (INR/hour)	104.58	104.58	261.45	
Repair and maintenance (INR/hour)	1.89	16.12	33.33	8.84
Cost of lubrication (INR/hour)	13.16	36.86	146.10	0.93
Miscellaneous cost (INR/hour)				3.54
Total cost (INR/hour)	**191.69**	**395.37**	**1,226.72**	**34.58**
Total cost (INR/tonne)	**191.69**	**395.37**	**817.81**	**28.82**
Production cost of briquette (INR/tonne)	1.433.69			
Capital cost (principal)	80,000	4,90,000	19,99,970	4,84,376
Average use/yr (hours)	2,120	1,520	6,000	2,740
Electricity tariff	INR 4.87/kWh			
Interest rate	12%			
Taxes and insurance	1% of principal			
Repair and maintenance	10% of principal			
Miscellaneous cost (INR/hr)	2% of principal			
Salvage value	10% of principal			

Source: Authors' analysis;(Purohit and Chaturvedi 2018; Punjab State Electricity Regulatory Commission 2019)

Table A6: Formulae used in the study

Farm to straw bank	
Parameter	**Formulae**
Chopper/ cutter-cum-spreader cost	$\frac{\text{(Rental + Labour + Fuel) X Field area (acre)}}{\text{Straw Produced in the field}} = \frac{293 \text{ X } 2.79}{7}$
Baler + raker cost	$\frac{\text{(Rental + Labour + Fuel) X Field area (acre)}}{\text{Straw Produced in the field}} = \frac{1367 \text{ X } 2.79}{7}$
Loading and unloading cost	2 X [(Man-hours required/tonne) X (Skilled labour charges/hour)] = 2×[3.48×52.29]
	$2 \text{ X } \left\{\left[\frac{\text{(Distance from straw bank) X No. of trips required}}{\text{(average speed (km/hr))}} \text{ X (Tractor + Trailer rent/hr)} \right] + \right.$ [(Distance from straw bank) X (No. of trips required) X ((Diesel rate (per litre))/(Fuel mileage (km/l)] $\left. + \left[\text{(Skilled labour charges/hour) X } \frac{\text{(Distance from straw bank) X No. of trips required}}{\text{(average speed (km/hr))}} \right] \right\}$ $= 2 \text{ X } \left\{ \left[\frac{10 \text{ X } 1}{15} \text{ X } 245 \right] + [10 \text{ X } 1 \text{ X } (72.21/0.71)] + \left[52.29 \; \frac{10 \text{ X } 1}{15} \right] \right\}$

Source: Authors' compilation

Farm to bank to end-user	
Parameter	**Formulae**
Residue cost	(Average farm to straw bank cost over 5 - 15kms) X 1.1(Moisture wight loss) X (Residue to Briquette or Pellet ratio) = 1228.63 X 1.1 X 1.3(Optional)
Storage cost	(Storage charges/tonne of residue) X (10% weight loss due to moisture) X (Residue of Briquette or Pellet ratio) = 800 X 1.1 X 1.3(Optional)
Processing cost (optional)	(Briquette processing cost/tonne) = 1003.83 (Pellet processing cost/tonne) = 1433.69
Transport charges	$\frac{\text{(Truck rental + Fuel + Driver(INR/km) X (Distance from straw bank to end-user)}}{\text{(Payload capacity for bales) or (Payload capacity for pellets and briquette)}} = \frac{40 \text{ X } 50}{5.77 \text{ or } 7}$
Loading and unloading cost	2 X [(Man-hours required/tonne) X (Skilled labour charges/hour)] = 2 X [3.48 X 52.29] (Bales) 2 X [(Labour charges/tonne)] = 2 X [67.32] (Briquette/Pellet)

Source: Authors' compilation

Image: iStock

Briquettes are preferred in large and medium-scale boilers, whereas pellets are widely burnt in small-sized devices, such as a pellet stove, furnace, and cooking range.

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