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Advanced Strategies to Mobilize Crop Residue to Replace Coal in India

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Abstract

Various published data show the amount of crop residue available annually in India may range from a low of 90 to a high of 180 million tonnes. Different types of crop residue are collected from farmers depending on the geography and crop pattern for instance, in north India rice straw and cotton stalks are collected while in central India soya husk and sugarcane tops are collected. Baling and transporting straw from the field, though appear to be an option for safe disposal, will be feasible only when alternate, effective and economically viable usage methods are identified and facilities and infrastructure for ex-situ management methods are created. One immediate short term use of the residue is to replace 5% - 7% of the 670 million tonnes of coal India currently consumes to generate power. The farmers will benefit from the sale of their excess crop residue. The scheme will reduce pollution due to residue burning practices. Replacing coal will cut the GHG emissions. The challenge is to mobilize the crop residue collection and timely delivery to power plants. The data and calculations in this monogram show that it is economical for the farmer to remove the crop residue from the field quickly by using modern balers, to pelletize the biomass in small-scale distributed pellet plants, to store pellets in the modern steel bins and finally to deliver the pellets to coal plants by using rail transport. The delivered cost is estimated at around Rp 6.78/kg. The Government of India encourages the power plants to pay at least Rp 10/kg for the delivered biomass in the form of pellets. The current monogram analyzes the organization of an efficient supply chain in the State of Haryana India to ensure a sustainable modern enterprise.

Keywords

India, Pellets, Power Plant, Coal, Ag pellets, Supply Chain, Logistics, Storage Bins, Rail Transport, Cost Estimates, GHG Emissions, Infrastructure

1. Introduction

Utilization of crop residues as a fuel for power generation will not only discourage in-field crop residue burning abating air pollution, but will also reduce carbon footprint of coal based power plants. The SPARC (Scheme for Promotion of Academic and Research Collaboration, Ministry of Human Resource Development, Government of India) project conducted a detailed analysis of the recent advances in bioconversion technologies [1]. It came to light that the advanced biofuel production from lignocellulose crops is still in its early development and validation stages.

IRENA [2] reports on advanced biofuels have indicated the status of bioconversion technologies. Most of the technologies progressed through the early stages of biomass conversion like gasification, pyrolysis oil production, and biogas production. The technologies for upgrading from these early stages to a more valuable bioproducts and biofuels require public support [3] [4]. The Government of India has recognized the urgency of dealing with climate change and air quality while having the well-being of the farming communities at the center of its policies. The Government has mandated the power plants replace a small fraction of their coal (5% - 7% on mass basis) with biomass especially rice straw to lower pollution and greenhouse gas emissions [5].

The present research outlines a pathway to produce pellets at the farm level and supply the pellets to power plants at a competitive price [6]. Annually, India produces an estimated surplus agro-residue of around 140 Million tonnes (Mt) in excess raw biomass after all conventional uses. Reference [7] analyzed the policies that govern the supply and demand for bioenergy in India and concluded that a timely management of biomass especially paddy straw is a major challenge. In Haryana, an area of 1.35 million hectares is under paddy cultivation producing 6.86 Mt (million tonnes) of straw annually. Half of the straw is burned contributing to the air pollution [8]. The Government of India is providing extensive financial support and services promoting the in-situ management of the straw to incorporate the excess straw into the soil for the benefit of conservation. Equally, the government has announced new measures to encourage the removal of excess straw and to produce value-added products and biofuels from the wasted straw. The bottleneck is the organization of a robust supply chain to manage the removal of straw from the field, and transfer it as a reliable feedstock to the user [9].

Garg [10] estimates that 26 crops produce 39 different residues in India out of this, cereals group contribute the highest amount of surplus residue of 89 Mt followed by others. Roughly 64% of rural households in India rely on firewood for cooking and another 26% rely on crop residue or animal wastes for other applications such as providing shelter, construction materials, and ground coverings. The excess residue remaining in the field interferes with the land preparation activities and sowing for the next crop. Korav *et al.* [11]

encourages the use of in-situ management tools to deal with excess straw but do not endorse the ex-situ options due to the higher cost. In the absence of equipment to incorporate the excess residue in soil and the slow decomposition of crops in the soil, the farmers have found the easy way of removing the excess residue by burning it.

Dhanda *et al.* [12] stated that in Haryana the reduction in number of burning events in 2018 decreased by 41% compared to 2016 and 29% compared to 2017. The reductions in burn were attributed to the increase in ex-situ activities. According to the Intergovernmental Panel on Climate Change (IPCC), the highest contribution to the amount of residue burned on the farm is from the states of Uttar Pradesh, followed by Punjab and Haryana. Among different crop residues, major contribution has been 43% from rice straw, followed by 21% from wheat straw, 19% from sugarcane and 5% - 9% from oilseed crops residues [13].

The *in-situ* activities encouraged farmers to refrain from burning their straw are producing favorable results. In the last four years, farmers have been practicing methods of incorporating straw into the soil and using zero tillage for seeding after rice harvest. The availability of the new equipment like super seeders, straw choppers, balers has contributed to the success of in-situ management of straw [14]. However, there is much room to reduce straw burning practices. To this end, the Indian Council of Agricultural Research (ICAR) formed a committee to analyze various ex-situ crop residue management options for their technical feasibility and economic viability. ICAR [15] identified that a solution to a speedy harvest and an orderly supply chain of the straw biomass is critical to co-firing biomass with coal. The speed of harvest and stacking bales are dictated by the length of the harvest season which may range from 3 weeks to 6 weeks depending on the cropping rotation system. This monogram develops an orderly flow of biomass from farm to pellet plant and from stored pellets to coal power plants. The flow of pellets is analogous to the flow of grain cop from the farmers' field to millers.

2. Harvest Timing

Two groups of crops are harvested in different seasons in India. The Kharif crops or summer crops that are growing during the rainy season and are harvested in late October to early November. Rabi crops that are grown during the dry season, are sown in October-November and harvested in Spring (**Table 1**). The exact harvesting dates differ from region to region. The October-to-March Rabi crop season accounts for nearly half of India's food production. In Punjab and Haryana, the paddy crop is usually harvested between the first and last weeks of October. Farmers then sow wheat from the first week of November until the middle of December. With only 10 - 15 days between the rice-harvesting season and the wheat-sowing time, farmers often burn the stubble to quickly eliminate the paddy stubble. When paddy is harvested by a combined harvester and thresher,

Table 1. Crop sowing and harvesting schedules in India.

Season	Time Period	Crops	States
Rabi	Sown: October-December Harvested: April-June	Wheat, barley, peas, gram, mustard.	Punjab, Haryana, Uttar Pradesh, NCT
Kharif	Sown: June-July Harvested: September-October	Rice, maize, jawar, bajra, moong, cotton, jute, groundnut, soybean	Punjab, Haryana, Andhra Pradesh, Telangana, Tamil Nadu
Zaid	Sown and harvested: March-July (between Rabi and Kharif)	Seasonal fruits, vegetables, fodder crops, etc.	Most of the northern and northwestern states

https://www.drishtiias.com/to-the-points/paper3/cropping-patterns-and-major-crops-of-india-part-one.

the machine leaves behind a significant length of straw and stubble on the field. This prevents other machines from sowing wheat seeds.

3. Straw Yield from Grain Yield

The ratio of straw to paddy varies, ranging from 0.6 to 1.4 depending on the height of the stubble left after grain harvest (**Figure 1**). The amount of rice straw taken off the field depends mainly upon the cutting height (*i.e.*, height of the stubble left in the field). The average mass of above ground straw is about 8 t/ha. The amount of straw yield then is 3.5 t/ha when the height of the cut is 40 cm and is 4.5 t/ha when the height of cut is 20 cm. The total straw removed without any stubble left is 8 t/ha [16].

Table 2 lists the average size of landholding in Haryana at 2.22 ha and in Punjab at 3.62 ha. The average size of the landholdings in the country is 1.08 ha. Almost 100% wheat straw in the two states is fed to animals and is not available for pelletization. Rice straw is not desired as animal feed because of its high silica content. Multiplying the average farm size by rice yield gives 7.1 and 15.6 t/farm for Haryana and Punjab, respectively. We may assume that the net biomass available for a pelletization process would be 50% of the quoted total biomass.

The data in **Table 2** provides a basis to calculate number of plants each with a daily production of about 20 tonnes, 7200 tonnes/plant or 1182 plants in Punjab and 314 plants in Haryana to process 50% of the surplus straw.

4. National Distribution of Biomass

Figure 2 shows the distribution of the biomass among Indian states [17] [18]. The bar chart also includes the biomass from forestry. The distribution of biomass is relatively uniform among states. The details of the available woody biomass are not available in the report. The states of Haryana and Punjab do not

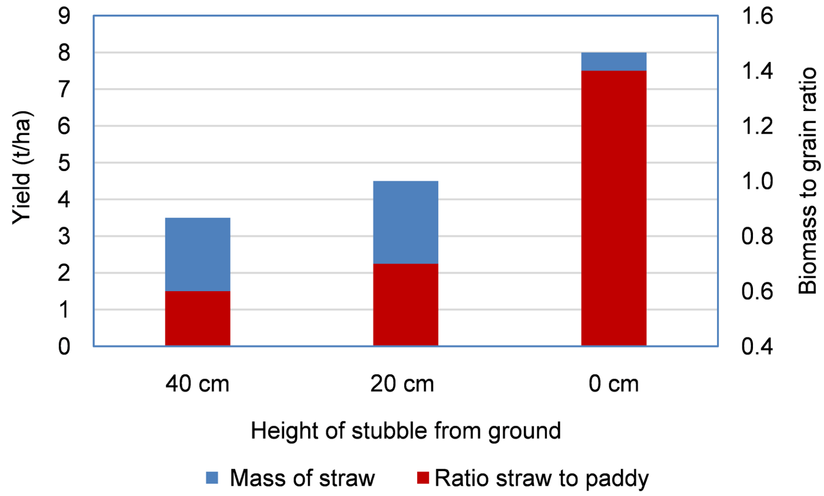

Figure 1. Straw yield and the ratio of biomass to grain for paddy as a function of stubble height [16].

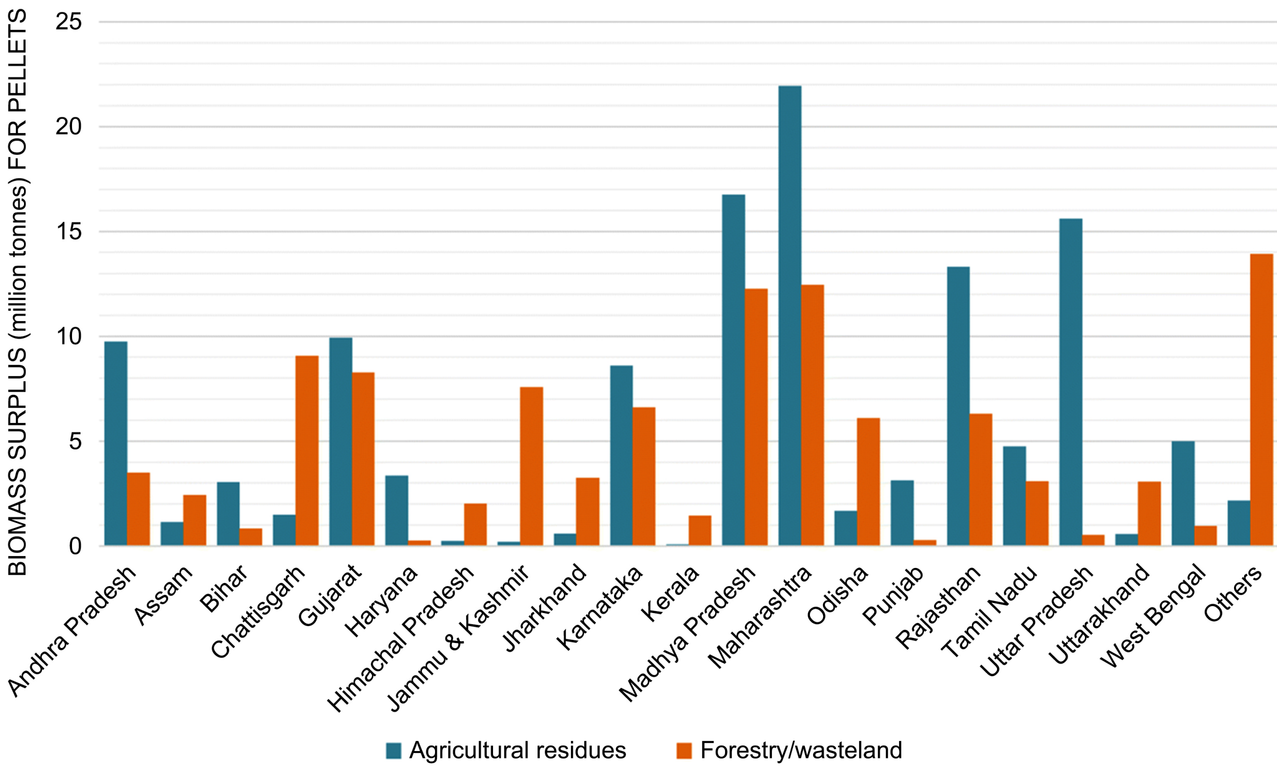

Figure 2. Distribution of agricultural and forestry biomass surplus among Indian states. Source [17].

Table 2. Yield (t/ha) of wheat and rice straw in the states of Haryana and Punjab. The number of farms and average size of the farms and an estimate of rice straw available in the states.

State	Wheat straw (t/ha)	Rice straw (t/ha)	Avg. farm size (ha)	No. of farms	Rice straw (t/farm)	Rice straw (Mt)
Punjab	5.1	4.3	3.62	1.09×10^6	15.6	17.01
Haryana	4.4	3.2	2.22	6.36×10^6	7.1	4.52

have much biomass from forest resources. The biomass is calculated from grain assuming that biomass is at 30% moisture content (wet basis). The biomass available is adjusted to 10% moisture content to suite the densification/pelletization. Generally wheat is used-up in animal feeding. Most of the available biomass is from rice straw and from sugar cane bagasse. The biomass at 50% availability is calculated at 182.9 million tonnes.

5. Biomass for Co-Firing

When a small amount of biomass is added to a coal flame, the reaction environment is primarily determined by the combustion of the coal rather than by the biomass kinetics [19]. Premixing crumbled biomass pellets and coal can enhance the combustion of the two fuels, whereas poorly mixed biomass and coal tend to burn independently at different rates. Flame stability has been found to be little affected by the amount of biomass added in all cases studied, provided that the addition is less than 20% by mass.

Government of India has issued a ruling to the power plants to reduce their alliance on coal by 5%. We use Haryana situation to estimate the daily and annual demand for coal. **Table 3** lists the existing power plants in Haryana and their power generation capacity. The power generation ranges from 600 MW to 1500 MW. The equivalent coal requirement can be calculated at a conversion rate of 1.927 MW per tonne of coal. The volume of coal usage for Haryana plants are estimated at 25,200 tonnes daily and 7,667,000 tonnes annually. In order to arrive at coal usage for each plant we calculated the fraction from each plant base on its rated capacity. We multiplied each fraction by the daily (25,200 tonnes) and annual (7,667,000 tonnes). To come up with the biomass usage at 5% of the coal,

Table 3. Power plants in Haryana, daily and annual coal and biomass requirements.

Capacity (MW)	Fraction of power capacity	Coal per year (t/y)	Coal per day (t/d)	5% biomass (t/y)	5% biomass (t/d)
Panipat Thermal Power Station II, Khukhrana Panipat					
710	0.177	1,357,000	4515	135,750	451
Deen Bandhu Chhotu Ram Thermal Power Project, Yamuna Nagar					
600	0.150	1,147,000	3815	114,718	381
Rajiv Gandhi Thermal Power Station, Khedar, Hissar					
1200	0.299	2,294,000	7631	229,436	763
Indira Gandhi Super Thermal Power Project, APCPL Jhajjar					
1500	0.374	2,868,000	9539	286,796	953
Overall					
4010	1.000	7,667,000	25,500	766,700	2550

we multiplied each of the coal usage by 0.05 and multiplied by 2 to account for the lower calorific value of biomass which is assumed half of the calorific value of the coal.

At present pelletized biomass in Haryana is supplied to co-firing in brick kilns. There are 2163 brick kilns in the NCR region of Haryana and 2200 brick kilns in Punjab. A kiln requires on average 200 tonnes of coal 5 to 6 times a year. The coal required annually for Haryana's and Punjab's kilns is almost the same as each state requires at 2.6 Mt/year. Using half of the calorific value for burning biomass compared to coal, more than 10 Mt of biomass could potentially be required annually to replace coal in the brick kilns of Haryana and Punjab. A 5% reduction in coal generates demand for 0.5 Mt/year of biomass pellets for each of the two states.

6. The Supply Chain

We envision that all of the biomass delivered to power plants and brick kilns would be in the form of pellets. The diameter of pellets ranges from 6 mm to 12 mm. The supply chain will consist of at least 3 distinctive activities (**Figure 3**), 1) farming to produce straw; 2) straw baling and delivering the bales to pellet plants; 3) storing and transporting pellets to the power plant. The actors involved in these three activities engage in the value chain from the farm to the final use of biomass. The farmers may bale the straw themselves or have a custom operator to bale the straw. The farmers or the custom operator may transport bales to the farmstead for temporary storage or directly to the pellet plant. The pellet plants that are usually in order of 1 t/h capacity may be stationary or mobile. The farmers may engage a mobile pellet plant to pelletize the straw bales at the farmstead.

A pellet plant or its agent may spot the bales and contact the farmer about acquiring the bale and transporting the bales to the plant site. Another option is that the biomass is chopped up at the farmstead and then transported to the pellet plant. The pellet plant with a capacity of 1 - 1.5 t/h will convert the biomass to the pellets. The pellets when of sufficient quantity are transported to the power plant or to a satellite storage. An aggregator may be involved in the phase of storage and transportation (**Figure 3**) Datta *et al.* [8] discusses a similar scheme for collection and distribution of crop residue.

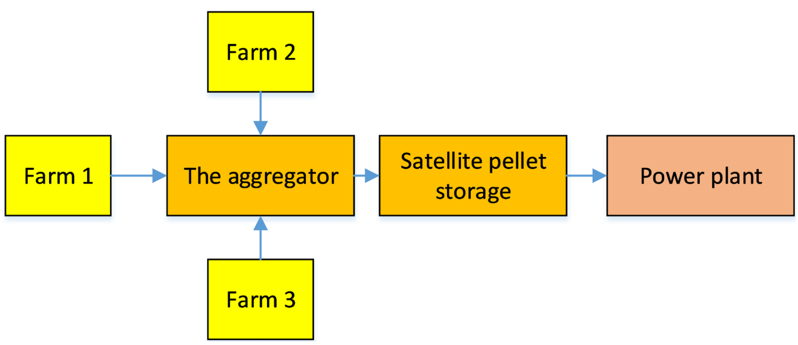

Figure 3. Gathering the straw, pelletization and transport of straw to power plant.

7. Bulk Density

Bulk density of rice straw is a critical factor in designing and operating handling of biomass. Bulk density, the ratio of weight of a bulk of biomass over its volume is often expressed in kg per unit volume m^3. **Table 4** lists the measured bulk density and its range for rice straw. Bulk density is used to calculate the mass ratio from blending two volumes. For example, a blend of 5% biomass with 95% of coal is often done using a front end loader that has a bucket with a specific volume.

A loose volume of biomass in the field typically weighs from 13 - 18 kg/m^3. As the size of the biomass decreases the bulk density increases. The bulk density of pellets is the highest at 600 - 800 kg/m^3. The bulk density of husks ranges from 86 - 110 kg/m^3. Transportation of pellets is more efficient in terms of the number of truck. Pelletized biomass takes less storage space. The bulk density of coal ranges from 700 - 900 kg/m^3.

8. Fast Removal of Straw from Field

The elements of a robust supply chain must be based on un-interrupted flow of goods and traceable transactions. Biomass supply is currently in its infancy and does not have a tested system of commerce nationally in India. The proposal here is to develop a supply chain parallel to the flow of food grains. To make this possible the loss biomass collected from field must be baled as soon as possible. **Figure 4** shows a modern baler, capable of making round bales of various sizes. The performance of the round balers is improving as the new balers do not need frequent stops and start to complete wrapping the bales [21]. Field experiments are required to develop baling operations especially when the moisture content of biomass is high. Round bales can shed the rain and thus have tendency to have a longer shelf life than the square bales. But a bale easily loses their roundness with time.

Table 4. Bulk density of rice straw when formed in different shapes [20].

Form of the feedstock	Density (kg/m^3)	Remarks
Loose rice straw in the field	13 - 18	Light material
Chopped 2 - 10 mm	50 - 120	4 - 5 times in bulk density due to smaller size
Bale Round	60 - 90	Baling packages the biomass
Briquettes 90 mm diameter	350 - 450	3 - 4 times in increase in bulk density of bales
Pellets 8 mm	600 - 700	Flowable easily handled like grain
Rice husks	86 - 110	May be pelletized

Kurinji and Kumar [18] worked out the cost of rice straw baling in Punjab. The operations were based on custom rates. **Table 5** lists cost calculations showing that cost of single bale is $16.57. The authors did not specify bale moisture content. If we assume straw at harvest 50% m.c. the cost of bale on a dry basis is $33.14/t. The price of a single bale delivered in Haryana is quoted at 2 Rp/kg or USD 36.60 which is close to the calculated cost of a bale in Punjab.

9. Pelletization

The palletization steps consist of breaking up bales to a size that can be fed to a hammer mill for grinding bales to a size less than 3 mm in order to make pellets. The suite of equipment consists of a loader to transfer bales from the stack to bale processor. The bale processor cuts the bale to a size preferably less than 100 mm. A feed processor that cuts the fibres to pieces for animal feeding can be used. The chopped biomass is fed to a hammermill for fine grinding. The suspended ground biomass is pushed up to a cyclone to separate the particles from air. The ground material is metered into pellet mill (**Figure 5**).

Table 6 lists the capital and operating cost items for a 1.5 t/h pelletization plant. The equipment includes a hopper bottom pellet bin, chipper grinder, flash dryer, hammer mill, blender, conditioner, feeder, pellet mill, conveyors, and a

Figure 4. A variable-size chamber baler makes round bales of different diameters.

Table 5. Cost of baling rice straw in Punjab according to [18].

Operation	Rp/t	USD/t
cutting and chopping	117	1.40
Raking and baling residue	595	7.14
Loading and unloading	364	4.37
First mile	305	3.66
USD/t at 50% m.c.	1381	16.57
USD/t at 0% m.c.	2762	33.14

Figure 5. A 1-2 ton pellet plant made in India (Courtesy Ecostan).

Table 6. Detailed cost of pelletization.

Capital cost	Power (kW)	Cost (USD)
Hopper bottom pellet bin 132 ton	0	22,000
Chipper Grinder	48	17,384
Flash Dryer with biomass burner	10	9089
Hammer Mill	48	14,822
Blender/conditioner/feeder	2	6000
Pellet Mill	69	31,169
Conveyors 4 units	2	60,000
Forklift	0	30,000
Installation (50% of the initial price)		95,232
Building		100,000
Total cost of capital		385,696
Cost (USD/t) 25 years, 8000 h/y		1.93
Variable costs		
Cost of Power (USD/t) at USD 0.10/kWh	180	18.00
Maintenance 3% of initial investment per year, 8000 hours at 1.5 t/h		0.96
Labor 2 person/shift, 3 shifts, $15/h each person, 8 hours, for 1.5 t/h		2.50
Total cost per hour (1.5 t/h)		23.39

*Conversion Rate: 1 Indian Rupee equals 0.012 USD as of 03-Mar.

forklift. The total cost includes $385,696 resulting in USD 1.93/t for capital cost. The assumed lifespan is 25 years, operating 8000 hours in a year for 1.5 t/h throughput. For variable costs the power requirement of 180 kW at USD 0.10/year yields 18 USD per hour. A total of 3% initial investment per year was assumed to cover maintenance and insurance. Two workers per 8 hours shift, for 3 shifts results in USD 2.50/t. The sum of initial and operating costs USD 23.39/t.

10. Pellet Storage

Pelletized biomass is best kept safe in upright steel storage bins. A steel bin may have a flat bottom with cross-wise augers for emptying. The bin equipped with an inverted cone (hopper bottom) stands above the ground (Figure 6). The bin is filled from top using auger, belt, or bucket elevator. The pellets (or any granulated material like grain or fertilizer) flow out of the bottom by gravity. A sliding gate controls the out-flow rate. Corrugated bins are more economical than the smooth walled bin. But the smooth walled bin is easier to clean. Either a corrugated or a smooth walled bin allows for installing aeration options. Maintenance for a steel grain/pellet bin is minimal. The bin should be cleaned after each unloading, inspected for insects and repairs made if needed. The expected useful life of a steel bin is estimated at 40 years [22].

Table 7 lists the low and high costs of material and installation for steel bins. The smooth surface bins with hopper bottoms are the most expensive. The cheapest bins are flat bottom but these needs means of unloading pellets.

Corrugated hopper bottom

Smooth wall hopper bottom

Figure 6. Hopper bottom steel bin for storing pellets.

Table 7. Estimation of cost of steel bins for storing biomass pellets.

Item	Corrugated hopper		Corrugated flat bottom		Smooth walled	
	Low	high	low	high	Low	High
Material ($/t)	98	138	49	118	138	177
Setup ($/t)	39	79	79	118	39	79
For a 50 t capacity ($)	6875	10,804	6384	11,786	8839	12,768
Annual cost (40 years) ($)	172	270	160	295	221	319
No weekly turnover in a year	52	52	52	52	52	52
Storage cost per week ($/week)	3.31	5.19	3.07	5.67	4.25	6.14
Storage cost per t ($/t, for 50 t)	0.07	0.10	0.06	0.11	0.08	0.12

11. Transport to Power Plant

One of the main advantages of pellets over other forms of biomass is their ease of loading and unloading. Hopper bottom covered railcars (**Figure 7**) are used extensively in modern grain handling operations and are suitable for handling biomass pellets as well. The particular covered hopper car shown in **Figure 7** has 90 m^3 capacity or approximately 63 tonnes of biomass pellets (bulk density of 700 kg/m^3). The Indian equivalent rail cars are "BOBRN" Rapid Discharge Wagon. The authors were unable to identify a covered model of this type of wagon at the time of preparation of the manuscript. On average, the freight rate of Indian railways per kilometer is Rp 1.6/(km·t), which is considerably cheaper than other modes of transport.

Haryana has 85 and Punjab has 135 loading locations. The rail network in the state of Haryana is shown in **Figure 8**. The State is covered by 5 rail divisions under 3 rail zones: North Western Railway zone (Bikaner railway division and Jaipur railway division), Northern Railway zone (Delhi railway division and Ambala railway division) and North Central Railway zone (Agra railway division). **Figure 8** shows the location of four power plants to which the rail lines could be used to transport biomass pellets. A future analysis will not be limited to one State. The rail network will allow the economic transport of pellets to regional and national power plants [23].

12. Summary and Conclusion

This paper outlines an advanced supply chain for collection, processing and delivery of crop residue to power plants. **Table 8** lists the itemized costs leading to the overall delivered cost of biomass pellets at USD 81.39/t equivalent to Rp 6.78/kg. The power plants are supposed to pay Rp 10/kg for the delivered biomass pellets (**Table 8**). There could be a net profit of Rp 3.22/t that could return to the actors along the supply chain.

Figure 7. Covered hopper railcars for transporting biomass pellets. https://www.trinityrail.com/.

Figure 8. The rail network in the state of Haryana shows the locations of power plants. The map shows typical straight line distances between biomass pellet collection points (depot) and the existing coal power plants in the State of Haryana.

Table 8. Summary of delivered cost of pellets.

Cost item	USD, Rp
Straw and baling ($/t)	33.14
Pelletization ($/t)	23.93
Pellet storage ($/t)	0.11
Transport (Re 1.50/km·t) for 100 km, ($/)t	1.80
Subtotal ($/t)	58.98
20% Contingency ($/t)	11.80
15% ROI ($/t)	10.62
Total ($/t)	81.39
Rp/t (0.012 Rp = 1 USD)	6782.70
Rp/kg	6.78

Although, there is a small window for the collection of crop residue it varies from 30 - 90 days in different parts of the country. The straw collection in the field is a major bottleneck in supply chain management hence, the use of balers may be encouraged for collection of straw from the field. There is a requirement of considerable area for the safe storage of bales for their utilization during off season periods. Hence the land available in the village may be undertaken on lease or Panchayat land may be made available for decentralized storage of bales.

Ultimately, transportation distance is a decisive factor in the economics of biomass pellets based power plants [24]. We conclude that in addition to accelerating the existing support for baler use, the sup[port should be extended to the establishment of the enabling small-scale pelletization operations, new storage systems for safe keep of pellets and managed marketing, and the necessary infrastructure for loading and unloading pellets for full utilization of rail systems.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Shahabaddine, S., Yadav, Y.K., Lau, A., Yadvika, Ebadian, M. and Verma, K. (2021) Identification of Techno-Economically Viable Crop Residue Utilization in India. *Journal of Sustainable Bioenergy Systems*, **11**, 94-104. https://doi.org/10.4236/jsbs.2021.112007

[2] International Renewable Energy Agenc (2019) Advanced Biofuels: What Holds Them Back? International Renewable Energy Agency, Abu Dhabi.

[3] Kalligeros, S., Kyriakos, M., Landälv, I. and van den Heuvel, E. (2018) Building up the Future Technology status and Reliability of the Value Chains. Sub Group on Advanced Biofuels Sustainable Transport Forum. Publications Office of the European Union, Luxembourg, 79.

[4] Kyriakos, M., Landälv, I., Waldheim, L., van den Heuvel, E. and Kalligeros, S. (2017) Building up the Future Cost of Biofuel. Sub Group on Advanced Biofuels Sustainable Transport Forum. Publications Office of the European Union, Luxembourg, 133.

[5] Ministry of Power (2022) Ministry of Power Issues Revised Policy on Biomass Utilisation for Power Generation through Co-Firing in Coal Based Power Plants. https://pib.gov.in/PressReleseDetail.aspx?PRID=1885751

[6] Shahabaddine, S., Ebadian, M., Rezaei, H. and Yazdanpanah, F. (2023) The Logistics of Production and Supply of Ag Pellets for Industrial Applications in Canada. *Journal of Sustainable Bioenergy Systems*, **13**, 40-55. https://doi.org/10.4236/jsbs.2023.131003

[7] Kothari, R., Vashishtha, A., Singh, H.M., Pathak, V., Tyagi, V., Yadav, B.C., Ashokkumar, V. and Singh, D.P. (2020) Assessment of Indian Bioenergy Policy for Sustainable Environment and Its Impact for Rural India: Strategic Implementation and Challenges. *Environmental Technology & Innovation*, **20**, Article ID: 101078. https://doi.org/10.1016/j.eti.2020.101078

[8] Datta, A., Emmanuel, M., Ram, N. and Dhingra, S. (2020) Crop Residue Management: Solution to Achieve Better Air Quality. The Energy and Resources Institute. https://www.teriin.org/

[9] Sarkar, S., Skalicky, M., Hossain, A., Brestic, M., Saha, S., Garai, S., Ray, K. and Brahmachari. K. (2020) Management of Crop Residues for Improving Input, Use Efficiency and Agricultural Sustainability. *Sustainability*, **12**, Article 9808. https://doi.org/10.3390/su12239808

[10] Garg, M.K. (2019) Bioenergy Potential from Crop Residue Biomass in India. Slide Presentation. Department of Processing and Food Engineering, CCS HAU, Hisar.

[11] Korav, S., Rajanna, G.A., Yadav, D.B., Paramesha, V., Mehta, C.M., Jha, P.K., Singh, S. and Singh, S. (2022) Impacts of Mechanized Crop Residue Management on Rice-Wheat Cropping System—A Review. *Sustainability*, **14**, Article 15641. https://doi.org/10.3390/su142315641

[12] Dhanda, S., Yadav, A., Yadav, D.B. and Chauhan, B.S. (2022) Emerging Issues and Potential Opportunities in the Rice–Wheat Cropping System of North-Western India. *Frontiers in Plant Science*, **13**, Article 832683. https://doi.org/10.3389/fpls.2022.832683

[13] Jain, N., Bhatia, A. and Pathak, H. (2014) Emission of Air Pollutants from Crop Residue Burning in India. *Aerosol and Air Quality Research*, **14**, 422-430. https://doi.org/10.4209/aaqr.2013.01.0031

[14] Mehta, A.K., Sharma, M., Sharma, K. and Yadav, P. (2018) Report of the Task Force

on Biomass Management. Confederation of Indian Industry (CII), New Delhi. https://www.cii.in/

[15] International Commission for Alpine Rescue (2021) Ex-Situ Crop Residuee Management Options. Indian Council of Agricultural Research, New Delhi.

[16] Gummert, M., Chivenge, P., Van Hung, N. and Douthwaite, B. (2020) Sustainable Rice Straw Management. Springer, Cham. https://doi.org/10.1007/978-3-030-32373-8

[17] Purohit, P. and Chaturvedi, V. (2018) Biomass Pellets for Power Generation in India: A Techno-Economic Evaluation. *Environmental Science and Pollution Research*, **25**, 29614-29632. https://doi.org/10.1007/s11356-018-2960-8

[18] Kurinji, L.S. and Kumar, S. (2021) Is Ex-*situ* Crop Residue Management a Scalable Solution to Stubble Burning? A Punjab Case Study.

[19] Jianjun, D., Sokhansanj, S., Grace, J.R., Bi, X., Lim, C.J. and Melin, S. (2008) Overview and Some Issues Related to Co-Firing Biomass and Coal. *The Canadian Journal of Chemical Engineering*, **86**, 367-386. https://doi.org/10.1002/cjce.20052

[20] Sokhansanj, S., Turhollow, A., Cushman, J. and Cundiff, J. (2002) Engineering Aspects of Collecting Corn Stover for Bioenergy. *Biomass and Bioenergy*, **23**, 347-355. https://doi.org/10.1016/S0961-9534(02)00063-6

[21] Sokhansanj, S. (2020) Baling Biomass: Densification and Energy Requirements. In: Holden, N.M., Wolfe, M.L., Ogejo, J.A. and Cummins, E.J., Eds., *Introduction to Biosystems Engineering*, American Society of Agricultural and Biological Engineers, St. Joseph, MI, 19.

[22] Jennifer, S. (2015) Grain Storage Considerations. Economics and Competitive Division, Agriculture Canada, Edmonton, AB, Canada.

[23] Anonym (2022) Average Freight Rate Per Metric Ton in Indian Railways from Financial Year 2006 to 2022. https://www.statista.com/statistics/741428/india-railway-freight-rate-per-metric-ton/

[24] Jacobson, R., Sokhansanj, S., Roeser, D., Hansen, J., Gopaluni, B. and Bi, X. (2021) Ancillary Impacts of Harvest Residue Pelletization. *Journal of Sustainable Bioenergy Systems*, **11**, 144-155. https://doi.org/10.4236/jsbs.2021.113011