CII-ITC Centre of Excellence for Sustainable Development

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CII Cleaner Air Better Life

CLEAN AND GREEN ECONOMY FOR AIR POLLUTION

ACTIONABLE SOLUTIONS FOR WASTE-TO-WEALTH FROM CROP RESIDUE

CII-ITC Centre of Excellence for Sustainable Development

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Actionable Solutions for Waste-to-Wealth from Crop Residue

Mohit Sharma, Aditya Bhuyan, Ishan Sahajpal

Technology Assessment Report
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PULP & PACKAGING SOLUTIONS
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EXECUTIVE SUMMARY

The need for farmers to shift from the dominant rice-wheat monoculture in India's breadbasket is a well-known and established view. However, this shift is yet to acquire momentum because of varied and complex reasons. Therefore, under the present circumstances, management of the post-harvest rice straw through in-situ (direct reuse by farmers) or ex-situ (use by other industries as raw / input materials) solutions are the only two practical choices for containing straw burning and the air pollution it causes.

In September 2020, we produced evidence of the changes taking place across 102 villages of Punjab and Haryana, where through an intervention led by CII, farmers experienced the benefits of adopting in-situ or ex-situ solutions to dispose of their rice straw.

This report further focuses on ex-situ solutions for rice straw management.

We estimate that in the states of Punjab and Haryana, 2/3rds of all the rice-straw can be repurposed through in-situ management. The remaining 1/3rd, which is approximately 13 million tonnes per harvest season, needs to be managed through ex-situ solutions.

This report presents actionable ex-situ solutions that are environmentally sound and of economic sense for all stakeholders. Some of them make more financial sense than others due to higher value addition in the process. However, market variables such as consumer awareness, price of raw material (rice straw), cost of aggregation, and pricing of the final product also impact what works. And therefore, a project's success.

We believe the rice straw aggregation model, detailed and evaluated in this report, when scaled, can address a host of these challenges and unlock other delivery models along with the entire supply chain of biomass. This aggregation model can add significant economic value to farmers and rural entrepreneurs, creating increased income and livelihood opportunities in these areas.

Our bottom-up analysis shows that the straw aggregation model can bring down the cost of ex-situ operations for the farmers by 34%, bringing it at par with other methods. This is a significant finding, and in our view, the Government should consider prioritising and incentivising straw aggregation. They can do this by -

1. Bringing straw aggregation under the priority lending schemes of nationalised banks (akin to bio-CNG)

2. Ensuring insurance cover is available to rural straw banks, insulating them from the risk of fire hazards

The Sustainable Alternative Towards Affordable Transportation (SATAT) initiative is an encouraging step from the Government to ensure offtake and a minimum guaranteed price for bio-CNG. However, ensuring the offtake of bio-fertilisers, a major by-product that accounts for 43% revenues in the bio-CNG model {Internal Rate of Return (IRR) at 29%}, will be crucial for its viability. Our analysis shows that when the bio-fertiliser offtake is just 50%, the bio-CNG project's net worth goes down by 72%, and the payback period nearly doubles.

Bio-fertiliser production can be of benefit to small and marginal farmers as well. A small composting pit of 30x10 ft can augment their annual income by INR 30,000 per year at zero capital cost and even without a microbial solution. Therefore, it is our considered view that crucial marketing support for bio-fertilisers can be provided as follows -

1. Market development assistance and schemes for promoting bio-fertilisers from crop residue akin to the City Compost Policy from the Government of India (GOI)
2. Involve the National Agricultural Co-operative Marketing Federation of India Ltd. (NAFED) and similar agencies with Pan-India networks to propagate and distribute bio-fertilisers through their outlets

The use of rice straw as animal feed in dairy farming has high potential, and an investment in a decentralised Total Mixed Ration (TMR) feed pellet plant is highly profitable, with IRR at 36%. But it requires meticulous planning by rural entrepreneurs for local filler material availability. Scaling this model can be encouraged via-

1. Dedicated schemes from National Dairy Development Board (NDDB) for knowledge support to rural entrepreneurs willing to set up TMR feed pellet units based on rice straw
2. Mass awareness creation for dairy farmers across Punjab and Haryana to remove misconceptions regarding the nutritional value of rice straw (non-basmati varieties) feed

Three key material uses of rice straw in construction are evaluated in this study - construction panels, blocks, and pulp. All three are found to have excellent returns with an IRR greater than 100%. As noted in the report, efforts are still underway to develop biochar reactors to improve the biochar manufacturing process's environmental performance by arresting over 90% of the emissions.

With these rapidly evolving and specific material uses of rice straw, new standards/certifications are required. In our view, these are -

1. Standards and certification for the use of crop residue or lingo-cellulosic materials in construction bricks and blocks
2. Standards and certification for torrefaction reactors to produce biochar and bio coal
3. Akin to the successful German model, certification for green manure and liquid bio-fertilisers from the Ministry of Agriculture
4. A separate protocol for testing procedures to certify green building materials

Besides the above, public-cum-private procurement of some of the rice-straw-based materials (with a demonstrated track record of field action) can be prioritised to address air pollution and avoid rice straw burning.

Finally, the Solid-fuel Pellets (SFP) model evaluated in this report is demonstrated to work from an operator and end-use market perspective, i.e., co-firing in industrial boilers (55% IRR) and thermal power plants (73% IRR). We found that the SFP model's key difference from other models is that it is highly price-sensitive, and operations become unviable if the rice straw's landed price exceeds INR 2/kg and pellet prices are lower than INR 4.5/kg.

Given the fact that necessary guidance has already been provided on co-firing by concerned authorities and regulatory agencies, we hope that the Government may consider -

1. Mandating that all Thermal Power Plants (TPP) start consuming at least 5% rice straw-based SF pellets acquired through competitive bidding
2. Notifying a mandate, akin to the GOI's fly ash directive, for the use of straw-based SF pellets manufactured within a certain radius
3. Allowing industrial boilers the choice to co-fire SF pellets and rice straw as long as adequate emission control systems are in place

1. BACKGROUND: AIR POLLUTION AND BIOMASS MANAGEMENT ECOSYSTEM

The massive quantities of rice straw burnt across Punjab, Haryana, and Uttar Pradesh in October and November every year contributes significantly to peak air pollution episodes across northern India. Atmospheric brown clouds from open agricultural burning coupled with unfavourable weather conditions (temperature inversion during winters and the blocking effect of the Himalayas) exacerbate the air quality situation across the already polluted and highly urbanised National Capital Region (NCR) and its surrounding areas (Saikawa et al., 2019).

Studies point to three prominent reasons for this:

1. The intensification of a rice-wheat monoculture across north India's agrarian states (Badarinath et al., 2006)
2. Narrowing time window[1] for the sowing of the Rabi crop because of groundwater conservation policies (Singh et al., 2020a)
3. The lack of an adequate biomass management ecosystem to handle surplus agricultural waste (CII- NITI 2018).

Research indicates a three-fold increase in acute respiratory infections for populations living in areas with intense crop residue burning. Eliminating crop residue burning across the northwestern states can avert disability-adjusted life years (DALYs) valued at INR 10,500 Crore over five years (Chakrabarti et al., 2019).

In 2020, overall crop residue burning incidences rose again. Rice-growing areas of Punjab, Haryana, Madhya Pradesh, and Uttar Pradesh witnessed the second highest[2] active fire detections (See Figure 1) for the post-monsoon period since the Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi NPP satellite collected data for the first time in 2012 (NASA Earth Observatory 2020).

Reducing surplus rice straw by moving away from rice cultivation to a more diverse and sustainable cropping system is the first choice to address crop residue burning. However, this requires system-wide changes and has not yielded results despite years of effort. Hence the practical option at this stage is to add economic value to this agricultural waste through direct reuse in the field (in-situ management) and recycling outside the field (ex-situ management).

In-situ management is a part of the broad conservation tillage techniques defined as any form of tillage that minimises the number of tillage passes, where soil aggregate disruption is reduced, and a minimum of 30% of the soil surface covered with residues (Carter 2005).

In-situ biomass management provides several benefits such as soil conservation, economic advantages due to reduction in crop establishment time and energy use, reduction in soil sheet erosion, reduction in nonpoint pollution, enhanced storage or retention of soil organic matter, and improvement of soil quality at the soil surface (Singh et al. 2018). Most of these benefits are established through the field data in our study (Sharma et al. 2020) of the CII Crop Residue Management Programme across 105 Punjab and Haryana villages. In these villages, over 87% of farmers adopted improved crop residue management practices based on the economic advantages they offered. However, in-situ biomass management has its limitations. Our field studies indicate that approximately one-third of farmers find it difficult to rely entirely on in-situ methods. These situations include:

1. In fields with hard soils where the feasibility of in-situ management techniques remains limited
2. In fields with sandy or sand-loamy soils or where alternate crop rotation (e.g., rice-potato-sunflower) is practised. Here in-situ management is either cost-ineffective or compromises the productivity of the subsequent crop
3. With farmers who want to provide a time gap between the harvest and rice straw application to the field.

In addition to in-situ management of biomass, the ex-

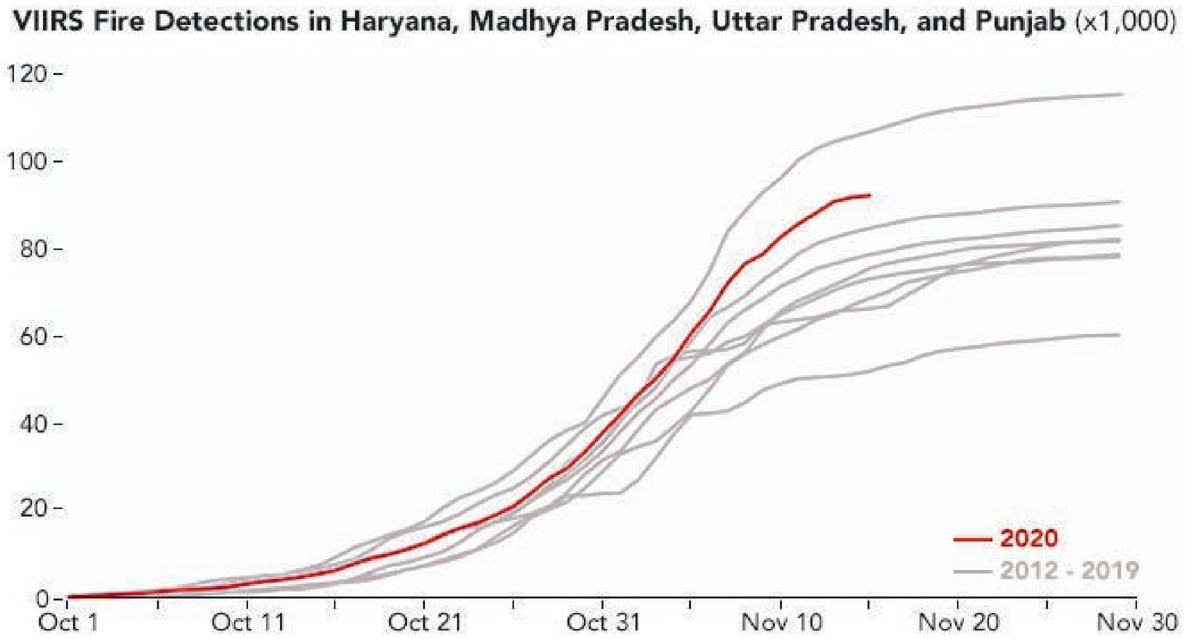
[1]25% increase in the post-monsoon rice crop production in Punjab during 2002-2016

[2]Despite the good adoption rate of in-situ management practice in the last few years

situ management system is an important back-up option. The scaling of ex-situ solutions and the accompanying supply chains and creating market awareness on these solutions are highly desirable.

Owing to its high silica and lignin content, rice straw is one of the most difficult biomass to process. This limits its economic viability in numerous applications compared to other kinds of crop residue such as wheat, cotton, and sugarcane, to name a few. The prime motivation for this study is to understand the economic viability of available ex-situ solutions. While most of them are still at a nascent stage, many show potential. Dedicated policy, technical and financial support is required to accelerate their fructification as viable options.

Figure 1. Active fire counts observed by Visible Infrared Imaging Radiometer Suite (VIIRS) sensor on the Suomi NPP satellite in October-November for years 2012-2020.



VIIRS = Visible Infrared Imaging Radiometer Suite
Source: NASA Earth Observatory (2020)

2. INTRODUCTION: ASSESSMENT OF EX-SITU MANAGEMENT SOLUTIONS

The screening and subsequent shortlisting of the various ex-situ rice straw management solutions for inclusion in this report were on their environmental merits and technology readiness. Following this, we undertook a detailed assessment of the shortlisted solutions. As most ex-situ solutions for rice straw were either under development or in field trials, their economic viability was questionable. Therefore, the key question for the research team was to determine whether the shortlisted solutions were economically viable. Detailed cost analysis of each helped shed light on the critical aspect of each business models' economic viability with respect to the market situation.

We found that price fluctuations and unsteady supply played a role in hampering new delivery models and technologies from gaining momentum. Figure 2 provides an overview of the overall biomass management system and the various ex-situ solutions that are a part of this system and assessed in this study.

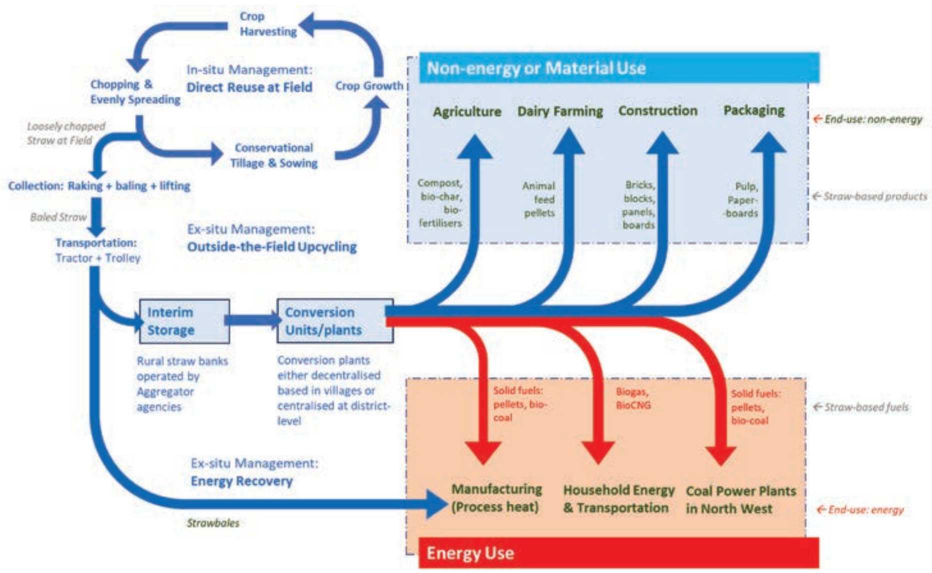
Section 3 provides a summary of the methodology and key strategies used to assess actionable ex-situ management solutions.

Key lessons from the field on how these solutions have fared under various entrepreneurs and assessments of the respective delivery models are in Section 4 under relevant subsections. These subsections focus on-

- Straw aggregation for delivering the biomass to the user facilities
- Agriculture and rural energy for specific rice straw applications within the rural economy, i.e., compost, biochar, animal feed, and bio-CNG
- Construction elements for the use of rice straw in building/construction
- Pulping and packaging solutions from pulping of rice straw
- Solid fuels and energy recovery focussed on pelletisation of rice straw to solid fuels and energy recovery in industrial boilers and thermal power plants.

Finally, in Section 5, the findings are concluded along with actionable recommendations.

Figure 2. Process diagram of biomass management system with specific elements under scope of this study.



Source: Cleaner Air - Better Life (2021) Analysis

3. METHODOLOGY FOR ASSESSING ACTIONABLE SOLUTIONS

The methodology for this study followed a combination of approaches. These included-

1. Field visits across Punjab and Haryana for interactions with rural entrepreneurs working towards developing delivery models on the ground.
2. A series of virtual Stakeholder Dialogues (See Figure 3) in May-June 2020 to understand the challenges of scaling the delivery models. Also, to get inputs from a wider group of stakeholders, including industry experts.
3. Data collection from select enterprises and a detailed cost-benefit assessment to understand the economic viability and thus the market readiness of these solutions.

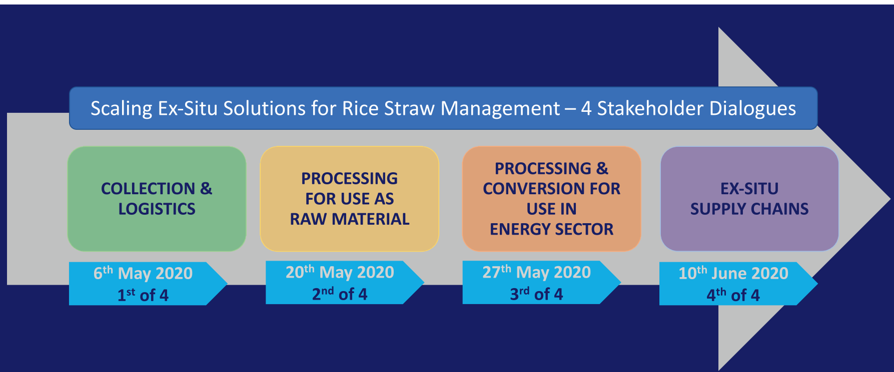
To build an understanding of the multitude of solutions rural entrepreneurs are practising, our research teams undertook field visits to multiple locations in Punjab and Haryana in the winter of 2019.

Further, we invited these entrepreneurs to the stakeholder dialogue series to present their ideas for scaling delivery models for ex-situ management of rice straw, focusing on the biomass management ecosystem's specific components.

We have used key indicators such as Pay Back Period (PBP), Net Present Value (NPV), and Internal Rate of Return (IRR) to assess the economic viability of various delivery models along the biomass management supply chains.

We compute PBP from initial investments and annual cashflows for these delivery models, but it does not reflect the money's time value. Therefore, to understand a project's viability from an investment perspective, we have modelled the Discounted Cash Flows (DCFs) for a realistic scenario. We have used DCF and NPV values to integrate the time value of money[3] into the annual cash flows. Due to the NPV method's limitation for comparing projects with similar initial investment outlays, we also computed project IRRs to compare different delivery models' economic viability. IRR is essentially the discount rate at which the NPV of the project reaches zero value, or cumulative DCF of the project equals initial investment. Subsequently, we performed sensitivity analyses on DCFs and NPVs to understand the impact of key assumptions or market situations such as the cost of raw material and the final product's price. We considered all cost components for building these investment models, e.g., land, labour, equipment/plant, raw materials, energy, chemical inputs, transportation, storage, packaging, etc.

Figure 3. Timeline of stakeholder dialogue series undertaken to understand challenges faced by enterprises to scale various technologies and delivery models for rice straw management in northwest region.



Source: Cleaner Air - Better Life (2021)

[3] Standard discount rate of 8% is utilised across assessed delivery models.

4. DELIVERY MODELS FOR WASTE TO WEALTH FROM AGRICULTURAL WASTE

Figure 4. Round Strawbales stacked in pyramid shaped rows at rural straw bank in Ludhiana, Punjab

4.1 Straw Aggregation

Across rural northwest India, straw aggregation is a business that is yet to be scaled as a lucrative business model. Aggregation is the backbone of the ex-situ biomass management ecosystem. It is a highly specialised business requiring experiential knowledge of best practices in collecting, baling, stacking, storing, and transporting the biomass to meet user requirements. These best practices include-

- Maintaining optimal moisture level[4] before baling chopped straw
- Applying appropriate compression force on the different layers of the bale
- Proper stacking (See Figure 4) with criss-cross layers and pyramid forms for round bales
- Maintaining a safe distance between rows for proper access and shielding from the risk of fire.

The above considerations[5] are essential to minimise biomass degradation (from rainwater seepage, microbial activity etc.), and the risk of fires during storage. A few credible enterprises, such as Farm2Energy and others, have demonstrated successful aggregation models across Punjab and Haryana.

Rural straw banks typically store between 1000 to 100,000 tonnes of biomass in the form of bales. As the rice harvesting period lasts only 15-20 days, interim storage at rural locations is crucial for the uninterrupted supply

[4]20-25% requiring drying of straw for two sunny days
[5]The list is not exhaustive for the scope of this study

of biomass to user entities. These include industrial boilers, conversion facilities for solid fuel pellets, bio-CNG plants, among others. (See figure 2).

As mentioned in the Executive Summary, we estimate that in Punjab and Haryana, while 2/3rds of all the rice-straw can be repurposed through in-situ management, the remaining 1/3rd needs to be managed through ex-situ solutions. Therefore, we estimate that between 100-1000 straw banks will be required to handle this kind of volume across these two states.

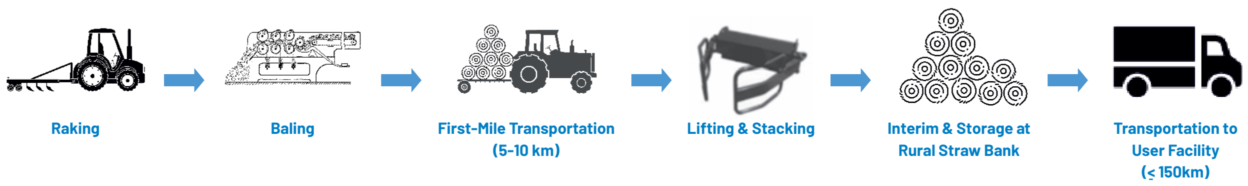
For this study, we have acquired the cost data from Farm2Energy. We then modelled the cost data from the operator's perspective.

The key steps involved in the straw aggregation (See figure 5) process are

1. Collection from the field (raking and baling)
2. Transportation from the field using tractor-pulled trolleys
3. Stacking and interim storage at the rural straw banks set up by aggregator agencies in the proximity of their catchment area (within 5-10 kilometres of central location)
4. Final transportation of baled straw to user facilities using trucks

For building a biomass aggregation case, the rural straw bank's capacity was assumed to be 60,000 tonnes of rice straw in a season or year, requiring a capital investment of INR 4.5 Crore. This investment includes the hardware (rakers, balers and fork-lifts) required by the aggregator for steps outlined in figure 5. For a rural straw bank this size, the catchment area would spread roughly over 100 square kilometres. For considerations of efficiency, we limited the distance for final transportation to the user facility to 150 kilometres and the average transportation charge to INR 525 per tonne of baled straw.

Figure 5. Process flow for straw aggregation model for the collection and uninterrupted supply of rice straw.



Source: Cleaner Air - Better Life (2021) Analysis

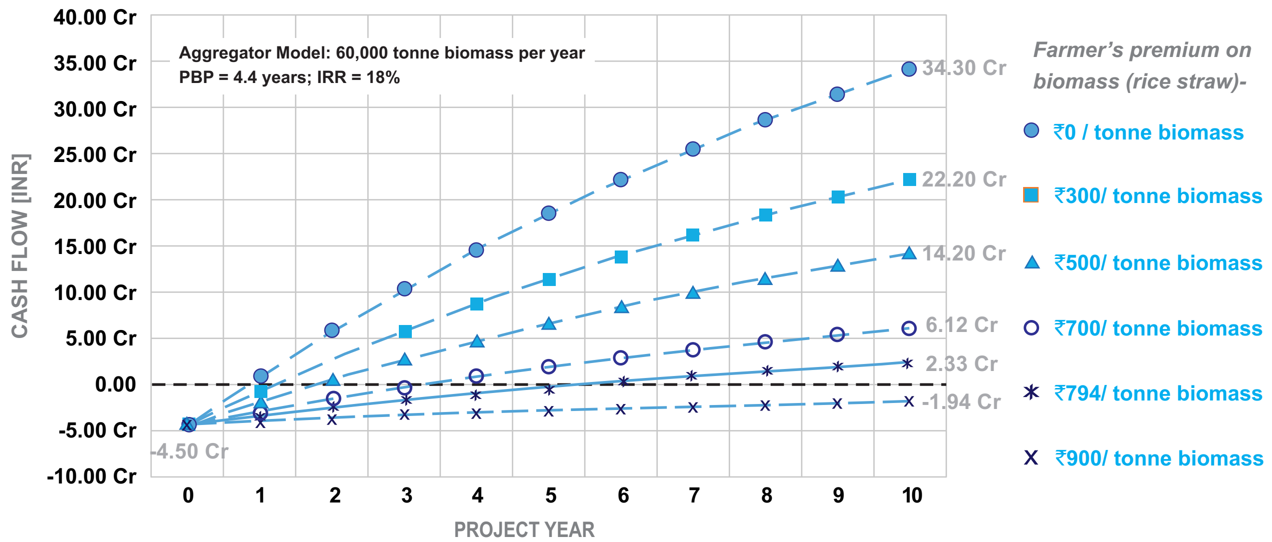
Based on the learnings from our study 'Impacts and Learnings of Crop Residue Management Programme' (Sharma et al. 2020), it costs the farmer INR 1985 per acre for getting rid of the agricultural waste from his field. Using a standard factor of 2.5 tonnes of rice straw per acre, it works out to INR 794 per tonne rice straw. We have considered this figure of INR 794 per tonne rice straw as charges by the service provider to clear the field of agricultural waste.

However, under the Farm2Energy aggregator model, the straw bank operator or aggregator does not charge farmers any money for this service. Hence the inherent assumption for modelling this process was that while the cost to a farmer for baling and evacuation service is INR 794 per tonne rice straw, a premium of a similar amount is paid to the farmer by the aggregator (Farm2Energy).

The team further analysed project cash flows for different scenarios, as depicted in Figure 6, where the farmer is being paid a premium that is either lower or higher than this value. It is worth noting that it costs the aggregator approximately INR 650 per tonne of biomass for operations ranging from field collection to stacking of bales at the interim storage or rural straw bank.

As depicted in Figure 6, the project is viable (or cumulative net present value of the investment over ten years is positive) if farmer premium is limited to a threshold value of approx. INR 850 per tonne of biomass. For the standard assumption of the farmer's premium at INR 795 per tonne, the project's net present worth is positive (INR 2.3 Crore), and the project is found to be viable.

Figure 6. Investment model for aggregation unit or rural straw bank with scenarios for different levels of farmer's premium on the rice straw.



PBP = Payback Period; IRR = Internal Rate of Return

Source: Cleaner Air - Better Life (2021) Analysis

Although the simple payback period is 4.4 years, discounted cash flow analysis indicates that the project yields positive returns in 5.5 years (at an 8% discount rate). From an investment perspective, this is a more realistic timeline for its break-even point. The internal rate of return for the project is 18% which is a useful indicator of its economic viability compared to other models whose initial investment outlay and cash flows are very different from the aggregator model.

Evidently, for scenarios where the farmer's premium is lower than INR 795 per tonne, the project is viable throughout, and its value increases with a decrease in this premium. If the aggregator charges the farmer the same rate as a private service provider of farm machinery (i.e., the full amount of INR 795 per tonne for their services or, in other words, zero premium), the project value at the end of 10 years is 7.6 times the initial investment (INR 34.4 Crores).

In addition to the above insights from cost analysis, there is a significant risk of a fire hazard at rural straw banks. Although rice straw is generated in a relatively short time window, it is typically stored year-round either at rural straw banks or onsite storage attached to user facilities. Extended storage periods also result in losses due to degradation of the rice straw and a documented 20% decrease in the Calorific Value (Singh et al. 2020b) within a year of storage. While this is a significant loss for energy applications, it is worth noting that even lower grade biomass can be utilised in selected material applications, e.g., manufacturing building/construction elements. These material applications are covered in the subsequent subsections.

4.2 Agriculture and Rural Energy

Direct reuse of rice straw at the farmer's field (in-situ management) is a preferable disposal method as it does not entail transportation of rice straw or its converted products over long distances. However, in-situ methods have their limitations for scaling to the entire region, and given the massive quantum of straw generation, we cannot deny the role of other methods in the overall biomass management ecosystem. There are several possible rice straw applications within the agricultural sector and rural economy besides its direct reuse in the field. They include-

- Conversion to green manure through composting
- Conversion to biochar through Pyrolysis
- Conversion to dry animal fodder through chopping/shredding or mixing it with supplements for conversion to Total Mixed Ration (TMR) for animals (with the further option of pelletisation)
- Conversion to biogas through Biomethanation and further purification of the biogas to bio-CNG

Composting is possible in multiple forms or configurations. The key methods can be classified as

1. In-situ composting: this form of composting is undertaken simultaneously with in-situ management. Inoculum with microbial culture is sprayed onto the field to accelerate composting, but this requires chopped and evenly spread straw on the field that is either retained as a mulch layer or incorporated into the soil.
2. Ex-situ pit composting: this form of composting is done manually outside the field in small pits with or without microbial inoculum and vermiculture.
3. Ex-situ windrow composting: this form of composting is done at scale outside the field using tractor-pulled farm implements and can be done with or without microbial inoculum and vermiculture.

Different composting techniques and microbial solutions are currently under trial with farmers. While all techniques have their limitations and benefits, this study focuses only on ex-situ techniques.

Pit composting requires near-zero capital but is labour intensive, requiring operations such as pit digging and compost bed turning, among other things. For a composting pit of 30x10 square feet, farmers can compost roughly about 30-45 tonne of rice straw every year (assuming 4- 6 batches in a year). Assuming a conservative price of manure at INR 3/kg and four batches in a year, net benefit to the farmer from setting up one such compost pit is estimated around INR 29,881[6]. This model can be scaled using degraded lands for large composting areas and mechanised means for turning the compost beds (windrow composting).

In our view, composting has significant potential for treating rice straw and generating value for farmers. However, there are barriers; limited land availability for composting and limited use of green manure by farmers being the prime ones. Acceptability of green manure amongst farmers need to increase. Some of these challenges for popularising and scaling bio-fertilisers have been revisited under bio-methanation. Bio-fertilisers are a significant by-product of biogas or bio- CNG production, and their limited use has a significant impact on the delivery model's cash flows.

Biochar, which is the main product of Pyrolysis, is used as a soil conditioner for agricultural land, either as a standalone application or along with fertilisers and green manure. As a soil conditioner, it has a high potential in northwestern India, where the soil is deficient in organic Carbon. Secondary literature mentions that if the straw residue is converted into biochar, we can recover 50% of initial biomass Carbon compared to only 3% during open burning (Venkatesh et al. 2018). Although a crude form of biochar kilns that can control 40-60% emissions compared to open burning exist, technology development for more efficient reactors that can further reduce emissions to 95% is still in progress. The proposed reactor from Takachar, once fully developed, will be able to consume 2-5 tonnes of rice straw per day. Lack of standards and certifications for such reactors (as it is neither a boiler nor gasifier) and marketing barriers for organic inputs are key challenges speculated by technology developers.

Animal feed in the form of (1) dry fodder and (2) balanced animal diet with the addition of nutrients {formally known as Total Mixed Ration (TMR)}, are two major routes through which rice straw can add value to the rural economy in northwest India and also help in reviving decentralised dairy farming.

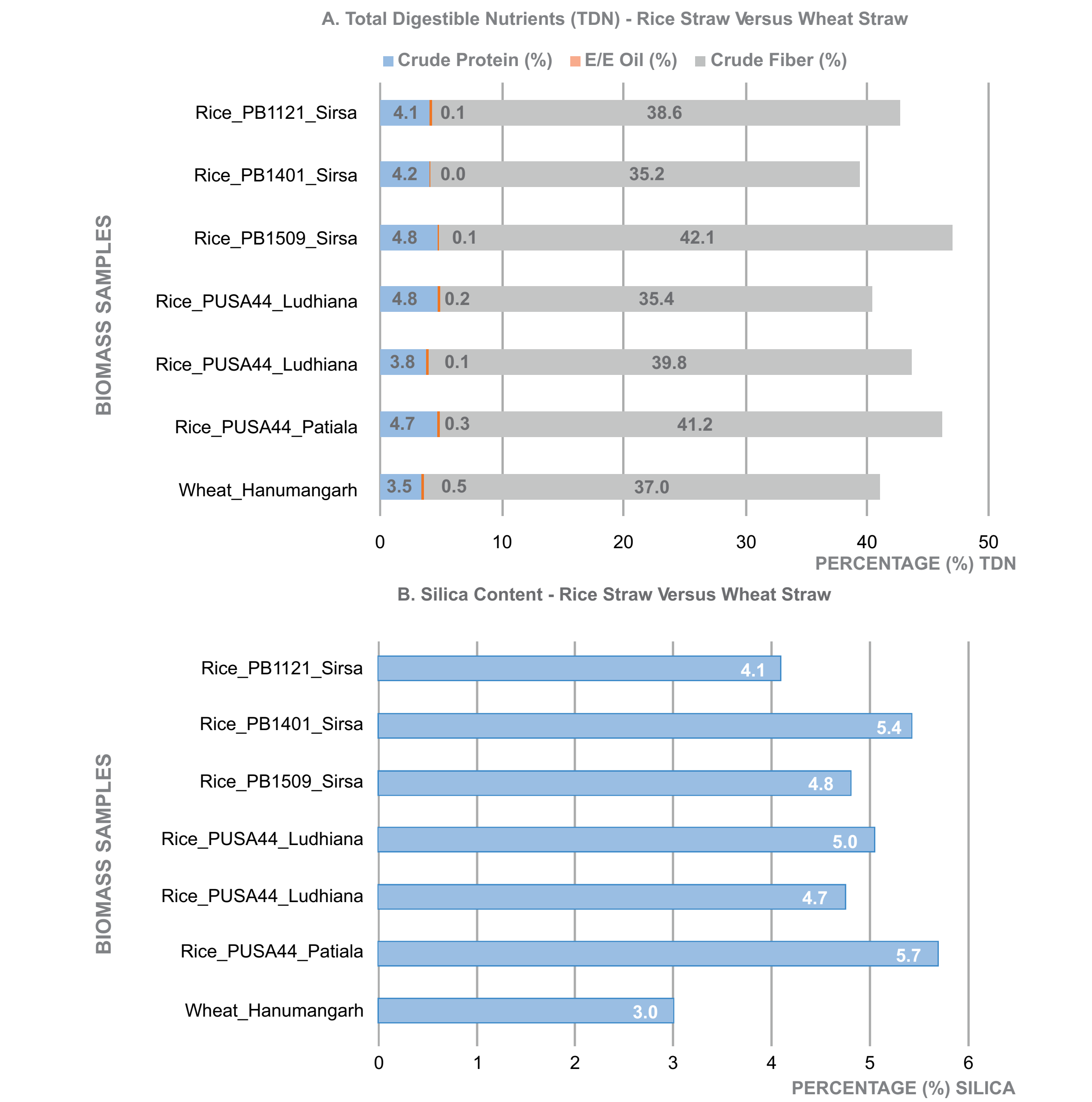
India faces a net deficit of 35.60 % green fodder, 10.95 % dry fodder and 44.00 % concentrate feed ingredients (IGFRI 2015). Surplus paddy straw can be used directly or by treating it with Protein or nitrogenous compounds (Kumar et al. 2014). In Punjab and Haryana, farmers have traditionally been feeding wheat straw to cattle, and their preference for wheat straw over rice straw is based on a flawed perception

[6] Total revenues and operational expenditure in a year are estimated at INR 63,840 and INR 33,959, respectively.

straw over rice straw is based on a flawed perception of poor nutrient value associated with rice straw (non-basmati varieties).

We analysed rice straw samples from Punjab and Haryana in the laboratory at Saras Dairy Plant in Hanumangarh, Rajasthan[7], for their nutrient[8] values. Preliminary analysis of the findings, summarised in Figure 7, shows us that the nutrient values are quite comparable[9]. This helps to bust the myth associated with the lower nutrient value of rice straw. Also, the Silica content for both rice and wheat straw is compared in Figure 7. Although Silica content is higher for rice straw (average 5% compared to 2% in wheat straw), it is acceptable for this application.

Figure 7. Comparison of total digestible nutrients (A) and silica content (B) of rice straw vis-a-vis wheat straw across northwestern region.



Source: Cleaner Air - Better Life (2021) Analysis

[7]Close to Haryana border
[8]Protein, fats and fibre
[9]Reference nutrient values of wheat straw from Hanumangarh are used for comparison.

Local entrepreneurs are already transporting rice straw bales from Haryana and Punjab to the bordering and straw scarce state of Rajasthan. They are able to fetch remunerative prices there, as dairy farmers of Rajasthan have no problem feeding rice straw to their animals. However, transporting bulky straw bales to far away distances is not very efficient as shelf life of straw bales is low. It is established that treated rice straw feed (compared to untreated rice straw) enhances milk and meat yield (Wanapat et al., 2009). Therefore, converted rice straw TMR pellets with other required nutrients or filler materials as a balanced diet is seen as an emerging delivery model.

In Hanumangarh Rajasthan, SARAS Dairy's plant (see Figure 8) has been producing TMR from wheat straw and piloted rice straw for TMR production with support from the National Dairy Development Board (NDDB), India. Our research team visited the plant in the winter of 2019. The capacity of this plant is 50 tonnes per day (tpd) TMR. Animal feed produced from this plant is supplied across Rajasthan in the form of pellets or briquettes. It has been beneficial to dairy farmers whose access to green fodder is limited as TMR feed helps increase milk quality and yield while maintaining the pH of the cattle's stomach. The key challenges faced by the plant engineers during the rice straw piloting phase and their learnings are summarised below-

- Due to the high Silica and fibre content of rice straw (See figure 7), grinding and feeder units face frequent jams causing the entire plant to breakdown. Wide and large feeders can solve the jamming problem.
- Metallurgy for the grinding units also needed adjusting with specialised blades for rice straw, and additional mechanical supports were needed for the conveyer feed systems.
- Optimal moisture is crucial, and the high moisture content in rice straw can also lead to challenges.
- There are misconceptions regarding the particle size to which rice straw should be grounded. Rather than grinding rice straw down to 1-3 mm, a particle size of 6-12 mm is adequate as it is suitable for animal digestion.
- The above consideration also reduces the chances of mechanical wear and damage in grinding and feeding units.

Figure 8. Total Mixed Ration (TMR) plant at SARAS Dairy in Hanumangarh, Rajasthan.

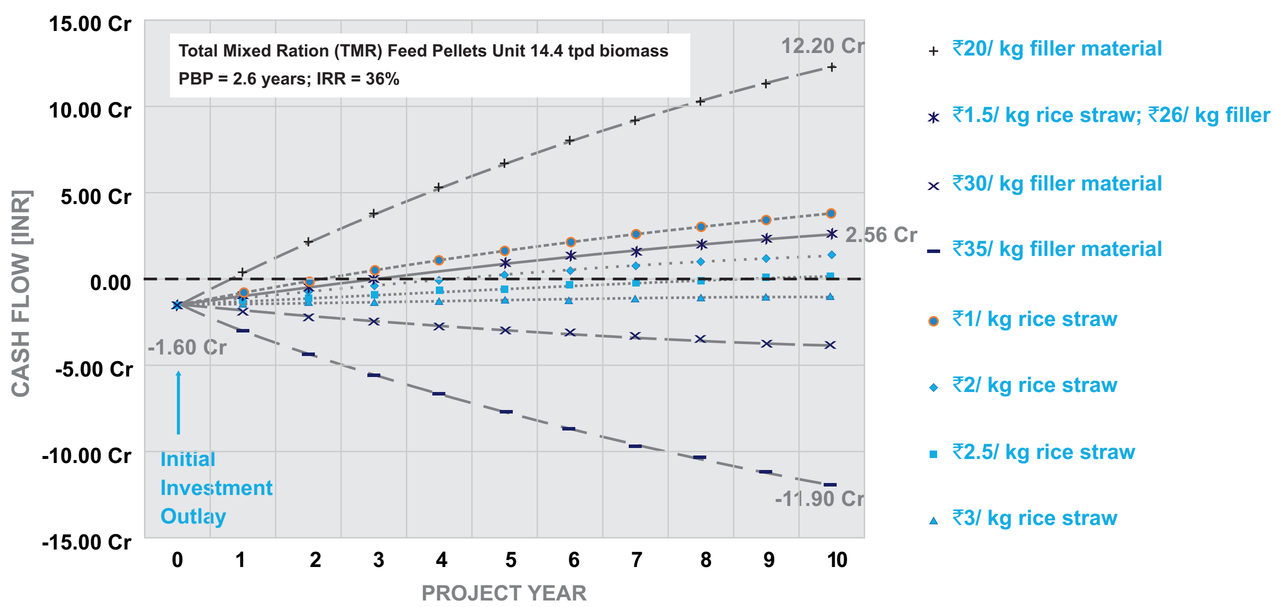
These summarised learnings are also applicable to entrepreneurs setting up units at smaller scales. Any rural entrepreneur can set up a TMR mixer to formulate TMR with proteins, mineral mixture, molasses, etc. The TMR produced can be in loose form or densified into pellets to increase shelf life, making it easier to handle and transport.

TMR mixers are available in the market in varying sizes from 2-8 m^3. Some can even be mounted to tractors that are >50 hp. As of 2019, there were 208 small TMR mixers (mainly based on wheat straw) operating in Punjab. The capital cost for these is INR 3-5 lakh with 50% capital subsidy[10].

For this study, a medium-sized (24 tpd) TMR plant was considered for developing the investment model. As shown in Figure 9, the capital investment needed for this scale is INR 1.6 Crore. Three key steps in the process include-

1. Grinding of rice straw to fine particles
2. Batch mixing with filler materials as per a predesigned formulation
3. Processing mixer in Roll-type extrusion pellet mill

Figure 9. Total Mixed Ration (TMR) feed pellet investment model with scenarios for different prices of raw materials: rice straw and filler materials.



tpd = tonnes per day; PBP = Payback Period; IRR = Internal Rate of Return
Source: Cleaner Air - Better Life (2021) Analysis

The proposed plant, which is under development, will consume about 14.4-tonne rice straw in a day, 60%[11] of the overall TMR formulation and 40% filler materials. The unit's annual cash flows are estimated at INR 62 lakh based on detailed data from the project developer at GBDSGNS Foundation based in Raikot block (Ludhiana, Punjab). Given that filler materials and rice straw prices are prone to market fluctuations, further sensitivity analysis on these was carried out. For an average price of filler materials at INR 26 per kg (refer to the TMR formulation in Table 1.) and rice straw at INR 1.5/ kg, the project Pay Back Period (PBP) is estimated at 2.6 years while based on discounted cash flow analysis, actual break-even is achieved in 3.5 years (with net present worth of INR 2.56 Crore). We can see from Figure 8 that the TMR pelletisation investment model is highly sensitive to the market prices of filler materials. With the average price going up from INR 26 /kg to INR 30/ kg, the project becomes completely unviable[12]. The project remains viable with rice straw prices ranging from INR 1-2 /kg.

[10]based on inputs at CII stakeholder dialogue series in May-June 2020
[11]By weight
[12]Negative NPV

Feed constituents and their prices vary from place to place depending on specific nutritional requirements of dairy animals and the local availability of filler materials. Therefore, appropriate design of onsite storage and location is essential for cost-effective intervention and access to market/consumers.

Table 1. Filler materials with prices for considered formulation of TMR pellets

S.N.	Filler Material	Composition [Percentage by Weight]	Price [INR/Kg]
1	Maize	10-15%	12-20
2	Millets	2-5%	50-80
3	Mustard	10-15%	20-30
4	Barley	3-5%	50-60
5	De - oiled Cake	5-8%	29
6	Urea	1%	10-15
7	Salt	1%	15-20

Source: Data collected from GBDSGNS Foundation

Bio-methanation is an important route for decentralised delivery models in an agrarian state to sustainably meet future energy needs. Our team visited the fully commercialised Sampurn Agri Ventures plant in Fazilka, Punjab (40 tdp capacity), a zero-liquid discharge plant that has been in operation for the last five years (See Figure 11). Green manure produced by the plant and approved by Punjab Agriculture University has shown significant benefits for improving crop yield and soil health in the field.

The bio-CNG investment model that we evaluated is based on the same dry digestor technology based on the dual-phase biomethanation process used by Sampurn Agri Ventures and the data collected from their technology provider. The analysed model processes rice straw at 70 tdp with a catchment area of 100 Square Km. For delivering purified and compressed bio-CNG, the capital requirement is INR 38 crore. Bio-methanation of rice straw can save a significant amount of import duties by reducing crude oil and gas imports. The reason why it is also part of the Government of India's Sustainable Alternative Towards Affordable Transportation (SATAT) initiative. Biofuels have the potential to reduce our fuel import bill by INR 100,000 crore (GoI 2020). However, it is a rather less known fact that bio-fertilisers (liquid bio-fertiliser and green manure combined) produced from bio-methanation can potentially substitute 40% of the total fertiliser consumption[13], reducing a burden of INR 20,000-30,000 crore spent by the Government of India on fertiliser subsidies. These facts need to be seen in the light that bio-fertilisers contribute to 43% of a bio-CNG plant's revenues, thereby playing a crucial role in the plant's economic viability. Annual cash flows from the assessed bio-CNG model are as follows-

1. Bio-CNG: INR 12.2 crore for 2.6 kilotonnes bio-CNG per year (57% of all revenues)
2. Manure: INR 5.6 crore for 14 kilotonnes manure per year (26% of all revenues)
3. Liquid fertiliser: INR 3.5 crore per year for 3500 kilolitre fertilisers in a year (16% of all revenues)

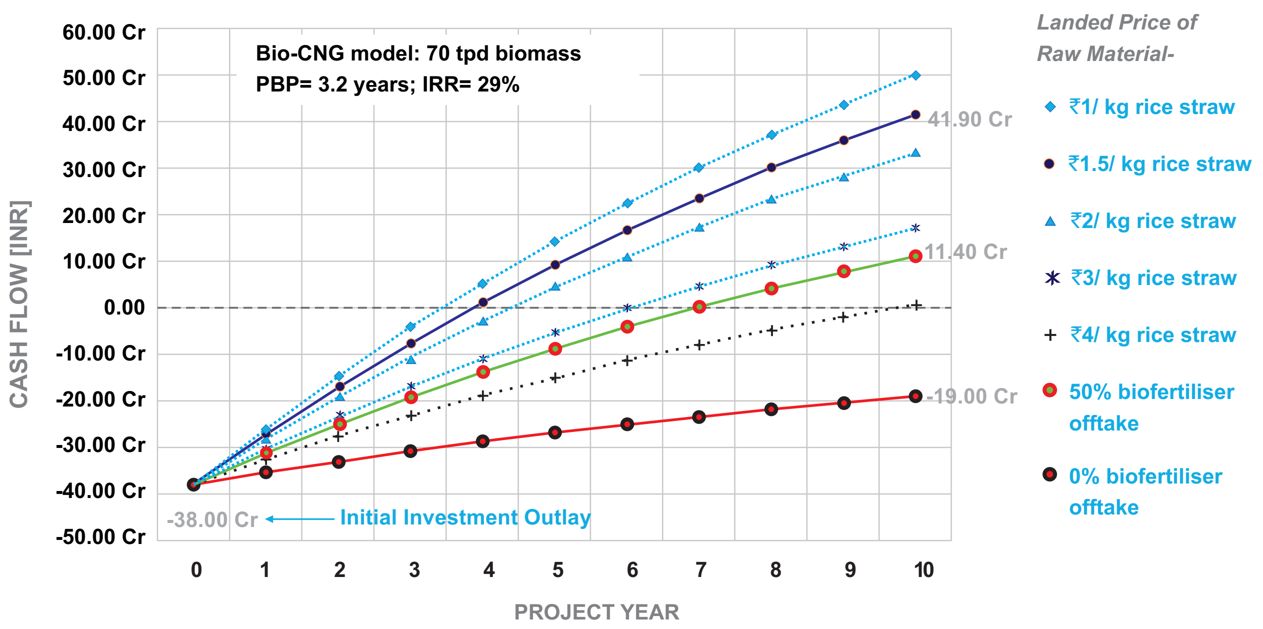
Therefore, our view is that promoting a bio-CNG model requires equal emphasis from an agricultural perspective, if not less, and an equal amount of efforts from agricultural agencies are required to prove this delivery model's viability and scale across northwest India.

As depicted in Figure 10, the project's net present value is INR 42 crore at an internal rate of return of 29%.

[13]Stakeholder inputs at CII Stakeholder dialogue series for scaling ex-situ solutions

As per the assured minimum price and guaranteed offtake of bio-CNG under GoI's SATAT initiative and assuming 100% offtake of the bio-fertiliser, it takes the project a little less than four years to reach the break-even point. The simple payback period is 3.2 years. However, if there is no offtake of the bio-fertiliser, the model becomes completely unviable, and we find that the NPV of the project will be INR -19 crore. Even if the plant can sell half the bio-fertiliser it generates (or fetch half the assumed[14] market prices), the project is just about viable at an NPV of INR 11.4 crore, and it will break-even in 7 years. Owing to the high economic value created by the bio-CNG model, it is relatively far less sensitive to fluctuations in rice straw prices compared to solid-fuel pellets (See Section 4.5).

Figure 10. Bio-CNG investment model with scenarios for raw material price and bio-fertiliser offtake.



tpd = tonnes per day; PBP = Payback Period; IRR = Internal Rate of Return

Source: Cleaner Air - Better Life (2021) Analysis

The analysis above clearly points to the difficulties of scaling this delivery model despite the excellent return rate of bio-CNG. There are inherent challenges in the offtake of bio-fertilisers, especially in Punjab and Haryana, where the farmers are predominantly disposed towards inorganic fertilisers, and the disproportionate subsidies on such fertilisers act as a deterrent for scaling bio-CNG.

[14] Manure at INR 4/ kg and liquid fertiliser at INR 10/ litre

Figure 11. Bio-fertilser offtake is crucial for viability of Bio-CNG model: Sampurn Agri Venture's Bio-CNG plant in Fazilka, Punjab with green manure from plant being cured in open as seen in the foreground

4.3 Construction Elements

Solutions for using agricultural residue in building/construction applications are fast emerging and are driven by demand for affordable housing and natural building materials with low embodied energy.

As rice straw is converted into construction elements, its application becomes Carbon neutral or Carbon negative depending on the actual use and specific context. In this study, two applications of rice straw in building/construction (See Figure 12) are being assessed-

1. Agrocrete bricks or blocks from rice straw, lime sludge and other industrial waste
2. Strawboards or construction panels from rice straw and non-formaldehyde-based binder

Although these applications are at a nascent stage of development, they are being demonstrated on the field. These are being assessed as a part of this study because –

- As floor space demand in India is projected to grow as much as seven times for urban residential buildings and three times for commercial buildings by 2050 (Rue Du Can 2019), these applications have a high potential to address the air pollution challenge likely to arise with the increased demand for construction materials in the future.
- These products can reduce global warming by avoiding the extraction of virgin materials in construction/buildings. Natural buildings can lower energy demand by improving the Building Envelop

Energy Efficiency (BEEE), but this varies with actual use case[15].

- Going a step further, they can store Carbon in building walls for hundreds of years and hence have negative carbon emissions over the lifecycle of their use.
- Degradation of biomass over longer storage periods does not limit its use, unlike in energy applications where degraded straw implies significantly lower calorific value. Also, it is possible to have wet storage (with water sprinklers), which reduces the risk of fire hazards at storage sites.

Figure 12. Agrocrete blocks and strawboard panels from Strawcture Eco

Picture on the right courtesy - https://www.thebetterindia.com/187863/uttar-pradesh-girl-quits-us-job-sustainable-homes-stubble-burning-india/

Agrocrete blocks are being assessed in this report for their economic viability. GreenJams BuildTech has developed these blocks as a patented technology. GreenJams uses rice straw, lime sludge, steel flakes, and other industrial waste streams in different proportions to manufacture Agrocrete. Agrocrete bricks have a compressive strength of 7.5 Megapascal (Mpa), lighter density (1400 kg/m^3) and a thermal-conductivity of 0.4 Watt per metre-Kelvin (W/m-K). Agrocrete blocks also demonstrate good water resistance with less than 10% water absorption. Traditional bricks have thermal conductivity ranging from 0.4-0.7 W/m-K, depending on the brick's size (Dondi et al. 2004). The compressive strength of conventional red bricks ranges from 3.5 to 35MPa. However, the widely used variety of bricks have strengths in the range of 5-7.5 MPa (BIS 2017).

The manufacturing process of Agrocrete blocks is simple and is similar to the conventional brick making process. A small plant manufacturing 1000 blocks a day costs approximately INR 5-6 lac in capital investment. Due to the simple manufacturing process, it is possible to design a hyper-local model and engage rural entrepreneurs.

Market awareness of the product is found to be a major challenge for scaling its use. Building codes also

[15] Agrocrete claims that every 'square metre' of wall made up Agrocrete blocks amounts to 38 Kg CO2e of carbon captured, 8 Kg CO2e GHGs saved annually due to improved BEEE.

partially impact product offtake in the market. The Bureau of Indian Standards' (BIS) IS: 2185, which provides the guidelines for building blocks/bricks, does not recognise biomass as a raw material for bricks/blocks, making it impossible to use the BIS symbol on Agrocrete blocks, even though they have comparable or even better characteristics as compared to red bricks.

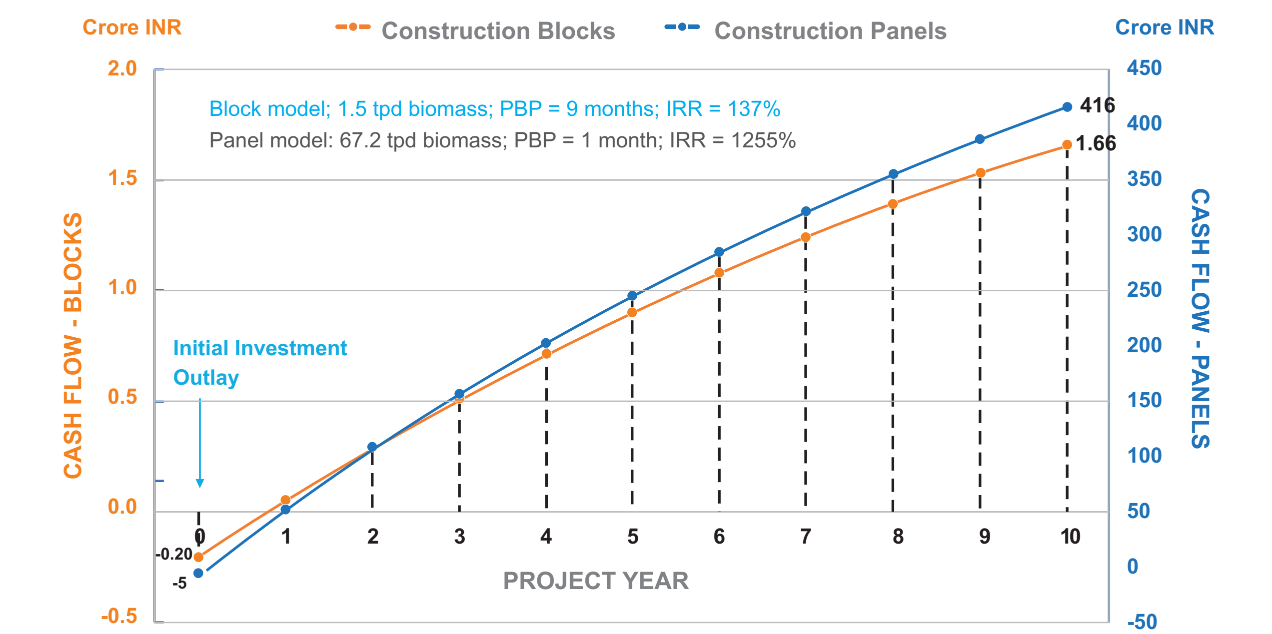
Strawboards and construction panels assessed in this study are produced by Strawcture Eco. They are made from rice straw and other agricultural residues as a replacement for wood or other concrete material. As of 2019, using these panels and boards, Strawcture Eco had constructed 15000 square feet across six Indian cities. Strawcture has an additional building capacity to manufacture 300,000 m^2 of the panel boards in 2020-21. Strawcture Eco is building 250-300 square feet sized houses under the Pradhan Mantri Awas Yojana and will have a capacity to build 2300 houses from the new factory. It has targeted to sell an additional 50,000 m^2 of panels directly to builders and architects.

The straw is processed into compressed boards using a non-formaldehyde-based binding solution[16] at a specific temperature and pressure for making these panels. Depending on its location, the plant can utilise various locally available biomass. The thermal-conductivity of the panels made from wheat straw, rice straw and sugarcane bagasse is approximately 0.09 Watts per metre-kelvin (W/m-K). The density of panels ranges from 750-1100 kg/m^3 depending on types-

1. Interior grade panel
2. Exterior grade panel
3. High-density flooring grade panel

While the panels for indoor use have approved quality/performance standards by BIS, the panels for exterior use were awaiting two tests to be completed at the time of writing this report. The price of an interior 18 mm panel made from rice straw is INR 50 per square feet; in comparison, a similar plywood panel costs INR 60 per square feet. It is worth noting that its cost is 15% lower than gypsum and cement boards. Although the Building Material Council of India has approved these panel boards, there is no formal information to back up the fact that bio-composite panels are similar in performance to conventional building materials.

Figure 13. Investment Model for Construction Blocks and Panels



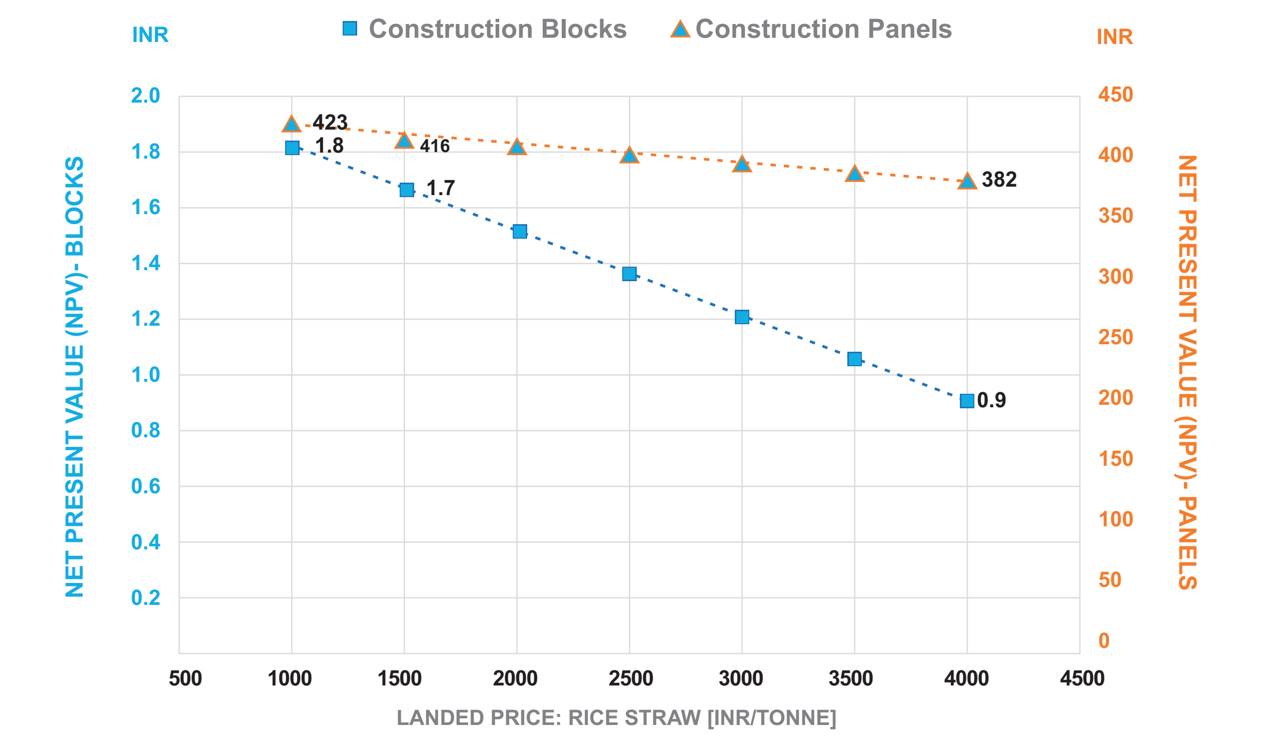
tpd = tonnes per day; PBP = Payback Period; IRR = Internal Rate of Return
Source: Cleaner Air - Better Life (2021) Analysis

[16] outsourced from third party

For both the described models, scaling is a challenge due to a lack of market opportunities owing to low market/consumer awareness. We evaluated investment models (blocks consuming 1.5 tpd biomass and panels consuming 67 tpd biomass) for both, based on detailed data collected from GreenJams and Strawcture. The results have been presented in Figure 13. It should be noted that although both models are shown in the same figure, discounted cash flows for the two models are not directly comparable, as the scale/sizes and initial investment outlays for both are very different. Both models demonstrate a high potential for scaling, yielding high returns and early break-evens (a few months), albeit under the assumption that all products are sold in the market immediately. However, that is not a realistic scenario, given the current levels of market and consumer awareness. Usually, these construction elements are produced as per requirement and not as a continuous process with 300 working days in a year, as assumed in this analysis. Nonetheless, it shows that both models have high potential if market opportunities exist.

Sensitivity analysis over the price of rice straw is shown in Figure 14. Here, unlike other investment models presented in this study, we found that both models are relatively less sensitive to the price of straw and NPVs remain positive (INR 0.9-1.8 crore for blocks and INR 382-423 crore for panels) for the entire range of landed prices (INR 1-4 per kg rice straw) used for this evaluation. Another observation that we can make here is that construction panels are less sensitive to rice straw price fluctuations between the two.

Figure 14. Sensitivity analysis over raw material prices



Source: Cleaner Air - Better Life (2021) Analysis

4.4 Pulping and Packaging Solutions

Once processed into pulp, rice straw can be converted to multiple products such as paperboards for packaging, disposable tableware, crafts etc. Besides addressing the air pollution problem, it can also be a solution to plastics pollution. Kriya Labs has developed the process of producing pulp from rice straw through a Chemi-thermo-mechanical process which has two crucial components-

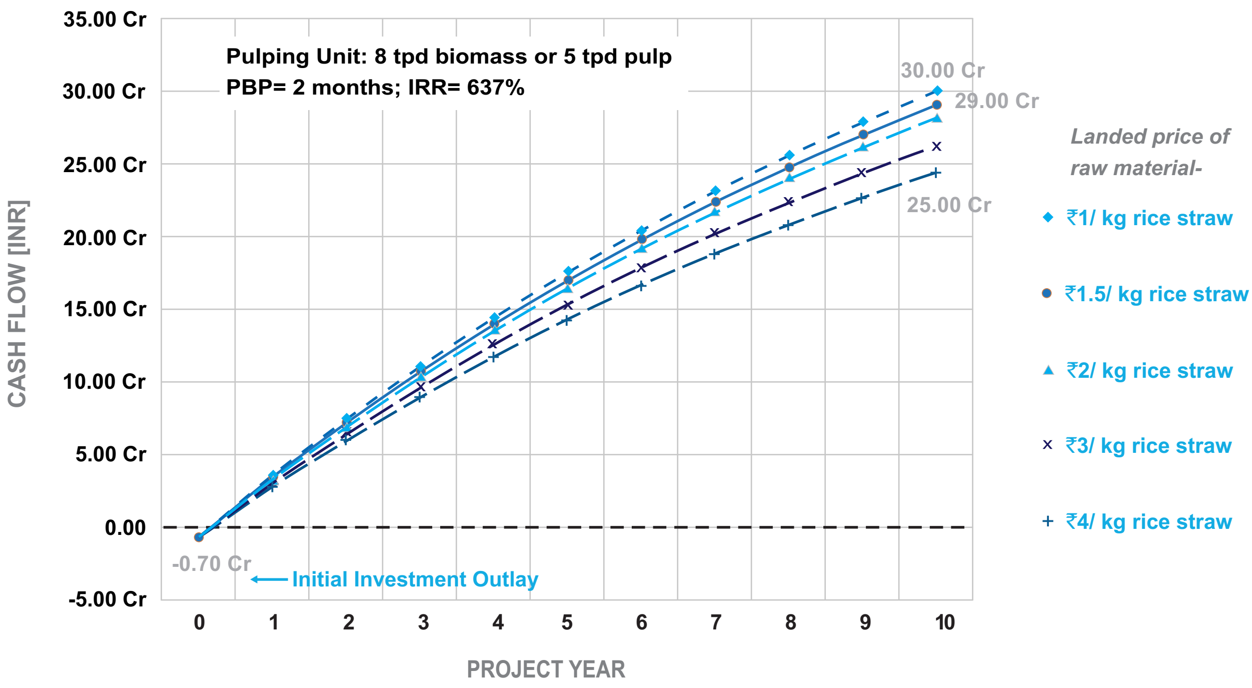
1. Pulping system
2. Water recycling system

Much like other material applications discussed in preceding subsections, chipped rice straw is first prewashed to remove any dirt and Silica. Softening of the chipped straw is the next step which involves treating it in a reactor with minimum doses of chemicals. The softened material goes through a mechanical refiner, which applies a shear on the fibres and separates them. This step turns the cooked material into pulp which is suitable for moulding into various forms and shapes required for a diverse range of products and packaging solutions.

The conversion ratio of straw to pulp is 0.62, which means almost 625 kg of pulp is produced with every tonne of straw processed. The pulp produced can be moulded into sheets, boards, disposable tableware or other packing materials. Since the whole process of pulping involves multiple washing steps, it is pretty water-intensive, and a water recycling system has a crucial role in the entire process.

The water recycling system deals with liquor generated at each step separately. All chemicals used in cooking are consumed in the process, and there is no need for any specific step for their removal, leaving only the organic and inorganic residues from the rice straw. The system is a combination of decanting and selective filtration where the liquor is removed from the pulp first in a particular proportion, and subsequently, the solid is removed from the liquor in a certain proportion. This solid is the only waste generated in the process and is an amalgamation of fine bits of lignin and Silica from the rice straw. It can potentially be used as a fertiliser or as a binding material in the construction industry. Treated water is analysed and is suitable to be fed back into the process to ensure zero liquid discharge.

Figure 15. Investment model for pulping unit and scenarios for landed price of raw material



tpd = tonnes per day; PBP = Payback Period; IRR = Internal Rate of Return
Source: Cleaner Air - Better Life (2021) Analysis

As depicted in Figure 15, the investment model and discounted cash flow analysis for a pulping unit producing 5 tpd pulp has been undertaken. The project has a short payback period of 2 months if 100% offtake of pulp is ensured at INR 40 per kg market price. The unit requires an initial investment of INR 70 lacs. It consumes 8 tpd rice straw and yields a high NPV of INR 29 crore (IRR at 637 %).

4.5 Solid Fuels and Energy Recovery

There are multiple ways in which rice straw's energy value can be extracted. The three significant pathways include-

1. Mechanical processing: grinding straw to finer particle sizes and further densification to meet the final user's needs
2. Thermal processing: based on process parameters and air supply, these are further categorised into Pyrolysis, Torrefaction and Gasification
3. Biological processing: Biomethanation and Fermentation to second-generation liquid biofuels

Multiple energy carriers generated from the above pathways can also interlink these pathways. Finally, we can also use these energy carriers for generating electricity. However, all of these excessively complex layers mean a significant loss of energy and efficiency with each step. Also, there are inherent challenges associated with handling and processing the rice straw for energy. These are –

1. Storage of biomass for year-round supply is essential, but baled biomass undergoes degradation with time, causing a dip in rice straw's calorific value. Evidence shows a 20% decrease in the calorific value over one year (Singh et al. 2020b). As rice straw's caloric value is already lower than other biomass types such as wheat, cotton, and sugarcane, this compounds the rice straw's energy use challenges.
2. The high silica and lignin content in rice straw implies that the cost of processing rice straw is higher compared to other biomass types and increases with reduction in particle size requirement by the consumer. This effect was documented for the case of dedicated bio-power plants and rice straw to bio-ethanol technologies in the CII-NITI (2018).

Therefore, two delivery models, i.e. 'solid fuel pellets' and 'direct firing of bales for energy recovery in industrial boilers', are considered affordable and actionable solutions[17] in this study. For reasons mentioned under point 1, rice straw needs to be either fired directly into the boilers (wherever possible) or densified into pellets.

Densification of biomass into Solid Fuel Pellets (SFP) has an advantage over loose straw due to higher density and better heat conductivity. Densification of biomass into Solid Fuel Pellets (SFP) also increases transportation and energy extraction efficiency at the end-use, whether it is an industrial boiler for process heat or thermal power plant for electricity generation in a purpose-built cookstove or oven.

Crushing, mixing, drying, grinding and pelletisation are key steps involved in the process which require specialised machinery. Experiences from A2P, a bio-energy start-up active in Punjab, show that –

- The use of innovative methods such as machine learning for mapping industrial boilers or the use of pellets and modified equipment helped reduce cost by 12%
- Focus on different kinds of biomass may ease some of the supply chain bottlenecks for year-round availability of feedstock and address rice straw's low calorific value issues.
- Wear and tear in the shredding unit (due to rice straw's higher silica content) is a significant cost factor for a pelletisation plant with a greater than 1 tpd scale. Therefore, research and development for the proper metallurgy and indigenous design of machinery are crucial, and collaboration with local entrepreneurs for customised solutions is desirable.

The calorific value of rice straw-based solid-fuel pellets is 3400-3500 Kcal/Kg which is comparable to washed coal (3500-3800 Kcal/Kg). It can, therefore, easily substitute coal in many applications. Pellets can further be torrefied for 25-30% higher energy value (comparable to imported coal) and a higher shelf-life, but this entails additional cost.

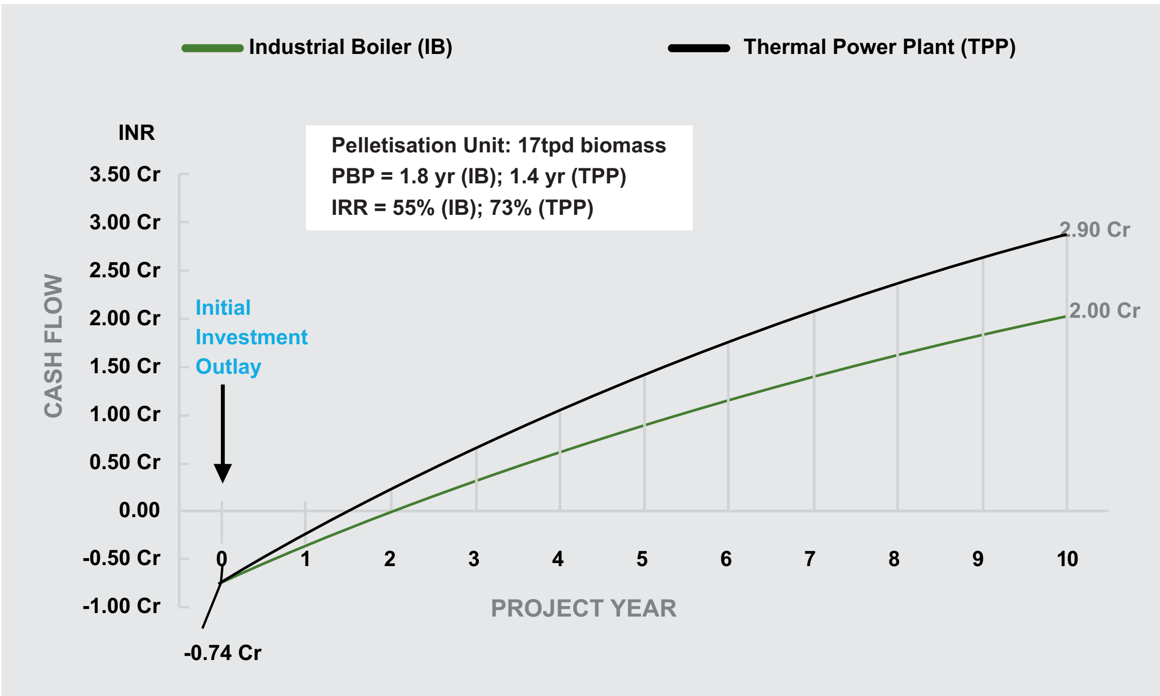
Various specific interventions have been made on this issue after the Ministry of Power's advisory (MoP 2017) directed power generators to utilise 5-10% rice straw by co-firing with coal in existing thermal power plants. MoP advisory also assures generators that any increase in the cost of generation will not be considered in determining priority or merit order for electricity dispatch. In this regard, guidance was issued by the Central Electricity Authority (CEA) in the same year (CEA 2017). The Ministry of New and Renewable Energy (MNRE) has further clarified that generators can even avail non-solar Renewable

[17]Refer Subsection 4.2 biomethanation of rice straw

Purchase Obligations (RPOs) (MNRE 2019). Subsequently, an order was issued by the Central Electricity Regulatory Commission (CERC) for a methodology to estimate electricity generated from biomass in biomass co-fired thermal power plants (CERC 2020).

NTPC invited bids for biomass pellets for two years' supply of 1,000 tpd in 2018 with a capping of the price at INR 5,500/tonne for conventional pellets and INR 6,600/tonne for torrefied pellets. However, NTPC received only 240 tpd material within the capping price. Subsequent tenders have been invited without the price capping. As per NTPC, supply constraints for pellets have not led to significant co-firing so far. The total potential within NTPC plants alone is estimated to be 20 million tonnes per annum at 10% co-firing. Technology readiness also exists in industrial boilers for the direct firing of rice straw. Several aggregators provide ready to fire feedstock to industrial boilers. Also, grated boilers or pulsating grate boilers have made it possible to directly fire bales in boilers without any operational challenges.

Figure 16. Investment model for pelletisation unit for use of solid-fuel pellets in industrial boilers with process energy requirement and coal-based thermal power plants



tpd = tonnes per day; PBP = Payback Period; IRR = Internal Rate of Return

Source: Cleaner Air Better Life (2021) Analysis

The investment model has been evaluated to assess the viability of pelletisation, and as depicted in Figure 16, two different scenarios with the use of pellets in industrial boilers and thermal power plants are plotted. Essentially, the key difference between the two models is -

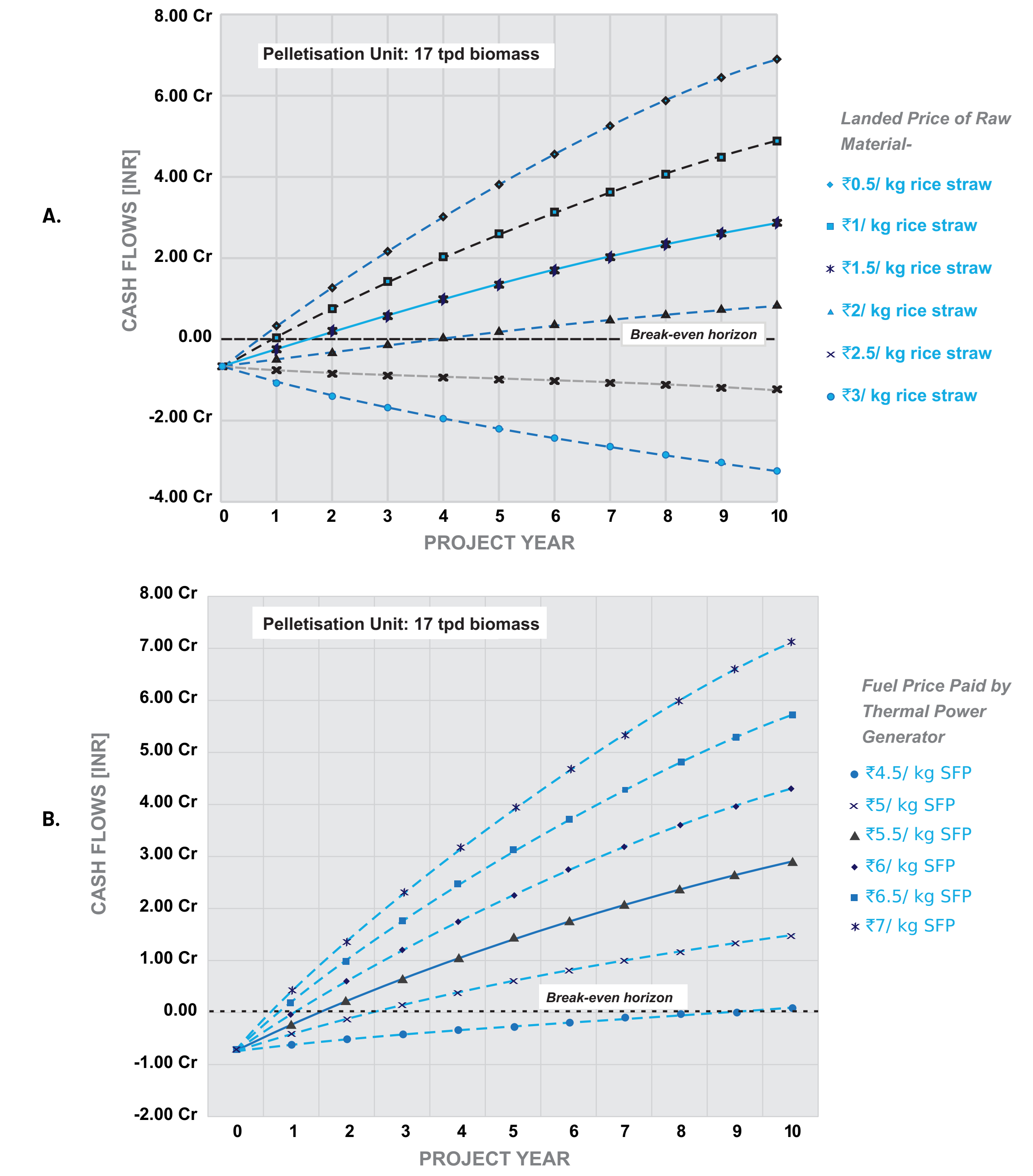
- Additional maintenance cost (assumed to 30% higher for TPP use case) to the operator for meeting the particle size requirement as detailed in the CEA 2019 guidance document
- The market price of SPF is assumed to be INR 5 per kg for the use case of industrial boilers (IB) and INR 5.5 per kg for the use case of thermal power plants (TPP)

It can be seen in Figure 16 that the project payback period ranges 1.4 - 1.8 years depending on SFP configuration. Despite higher maintenance cost, the TPP use case's payback is marginally higher than the IB use case. The project NPV for this pelletisation unit (INR 74 lac capital investment) is INR 2 crores and 2.9 crores for industrial boiler use case and TPP use case, respectively. Further, in figure 17, sensitivity analyses have been performed for the use case of TPP over different-

- Landed rice straw prices for the operator of the pelletisation unit
- Price of solid fuel pellets paid by thermal generators

We can see that the project's discounted cash flows in Figure 17 are very sensitive to both of these market prices. The project becomes completely unviable for rice straw prices over INR 2 per kg and pellet prices lower than INR 4.5 per kg.

Figure 17. Sensitivity analysis for (A) landed price of rice straw and (B) solid-fuel pellet price paid by thermal power generator



tpd = tonnes per day; SFP = Solid Fuel Pellet
Source: Cleaner Air Better Life (2021) Analysis

5. KEY FINDINGS AND RECOMMENDATIONS FOR SCALING SOLUTIONS

Key findings of the delivery models discussed throughout Section 4 point to special considerations and customisation required in the equipment for handling and treating rice straw from the northwestern states. This is due to the high lignin and silica content of the rice straw. However, the biomass management infrastructure, which is suited to rice straw, can handle almost any crop residue. Also, there is a definite need for more entrepreneurs from diverse backgrounds to join and pool skill sets to overcome technological barriers.

Straw aggregation is a specialised business as it requires a wide array of best practices (See Section 4.1) to be integrated into the business model and needs robust quality control to meet the requirements of the user facility. This delivery model will be able to make an economic case for farmers as well as rural entrepreneurs. Economic viability exists without even considering any capital subsidies for balers, and the venture is profitable with an Internal Rate of Return (IRR) at 18% and benefits to farmers worth INR 1985 per acre. It is, in fact, the only actionable model which could significantly bring down the cost of ex-situ management at the farmer's end to INR 2924 per acre (from INR 4629 per acre under the conventional renting model); which is close to the cost of the route which involves crop residue burning (INR 2948 per acre). Straw aggregation can serve as the backbone of all subsequent ex-situ management operations, and it needs to be brought under the priority lending scheme of national banks and, to make sure that business risks of the enterprises are covered, under insurance schemes as well. Depending on the size, between 100-1000 rural straw banks are needed across Punjab and Haryana. With a specific scale (60,000 tonnes biomass per year) of the aggregation model considered in the analysis, approximately 200 rural straw banks would be required across the two states.

The report presents specific cases of composting, biochar, animal feed and bio-CNG, which can add significant value to the rural economy. Scaling of composting, biochar, and bio-CNG requires promotion and mass awareness among farmers on bio-fertilisers for agriculture. The use of green manure remains limited in agrarian states. Our analysis shows that even without using any significant capital or microbial solution, the farmer can easily earn INR 30,000 in a year with a small composting pit of 30x10 ft. Composting is especially relevant for small- marginal farmers and can even be scaled with specialised equipment on degraded lands.

Standards and certifications for reactors producing biochar do not exist in the country. This affects how biochar technologies evolve in the future. These standards and certifications need to be carefully defined and designed in consultation with technology developers. Also, biochar is facing marketing challenges akin to the challenges faced in green manure and bio-fertilisers. This is due to the limited use of biochar by farmers, owing to their existing perceptions and heavy reliance on inorganic fertilisers.

Non-basmati varieties of rice straw are already being used as animal fodder/feed in India's eastern states. Rice straw from Punjab and Haryana is even being transported to the neighbouring state of Rajasthan and sold to farmers who face scarcity of straw. There are perception issues among farmers in Punjab and Haryana, which hinder them from adopting rice straw as a diet for their cattle. Our rapid analysis of a few rice straw samples from Ludhiana, Patiala and Sirsa geographies confirm these misconceptions. We found that values of various nutrients such as proteins, fats, and fibre in rice straw were comparable with wheat straw. A business model (24 tpd pellet feed based on rice straw) being developed by rural entrepreneurs at the GBDSGNS Foundation in Ludhiana was considered for evaluating this use case. The TMR feed pellet project has good viability with IRR at 36% and achieves break-even in 3 years. This model is viable for a landed rice straw price less than or equal to approximately INR 2.5 per kg and is also sensitive to the costs of filler materials used in the TMR pellets. Even slight fluctuations in the prices of filler materials (which depend on local availability) could render the TMR feed pellet project unviable, and hence project viability will depend on location. While the standard assumption of the average price for formulation used in the model is INR 26 per kg (filler materials), the project becomes unviable at INR 30 per kg.

Bio-CNG can be a great source of clean energy for the rural economy, and the assessed model has been found to yield good returns with an IRR of 29%, assuming an assured offtake of bio-CNG and bio-fertilisers produced during the operation. Guaranteed offtake exists only for bio-CNG (under bio-fuel policy by the Government of India). We found that with no offtake of the bio-fertilisers produced in the process, the bio-CNG model becomes completely unviable with a negative NPV (INR -19 crore). Even with a 50% offtake of bio-fertilisers, the project's net worth reduces by 72% and the payback period nearly doubles.

Therefore, the promotion of green manure and bio-fertiliser from agricultural waste or crop residues needs to be the focus of Government policies for unlocking the potential of three technologies: composting, biochar and bio-CNG. We are making the following recommendations -

- Green-manure quality certification guidelines, akin to the successful German model, are needed from the Ministry of Agriculture
- National Agricultural Co-operative Marketing Federation of India Ltd. (NAFED) and similar agencies should be roped in to propagate and distribute green-manure through their Pan-India network of outlets

We have presented three key, albeit less popular, cases for giving rice straw a new life and converting it into high value-added products in this study. Typically, crop residue is seen as a waste, which is why harnessing or recovering energy from rice straw seems like a logical choice. The study finds that material applications of rice straw are equally well suited when compared to energy usage. This is both a result of the inherent properties of rice straw and the nature of these processes. Some of these processes, e.g. construction blocks, allow for degraded/wet biomass and are not impacted by lowering of its energy value over time. With a proper formulation, rice straw makes strong construction blocks whose compressive strength is more or comparable to the commonly used red bricks in India. Insulation properties of construction elements from straw are also far better than conventional materials, and their greenhouse gas footprint is either neutral or negative, depending on the use case.

Construction and pulping models evaluated in this study are highly desirable from an investment perspective and can substitute virgin materials in numerous applications. Our analysis finds that construction panels, blocks, and pulp from rice straw have IRR greater than 100%, albeit with assumptions that all these products (blocks, panels and pulp) are sold at prices lower or equal to conventional products in the market. These three models are also least affected by fluctuations in the prices of rice straw. In our view, market awareness related challenges are the key barriers when it comes to scaling the use of rice straw in the manufacturing of construction elements and hence public/private procurement of these materials and other ways of their promotion will be pivotal for the success of these models in future.

Although standards for construction panels or strawboard exist, standards for crop residues or lignocellulosic materials in construction bricks/blocks do not exist in the country. As a result, blocks/bricks from crop residues are also not eligible for the Bureau of Indian Standard's (BIS) eco-mark. Even if standards exist, as is the case of panels, it takes a long time to get green products certified, and separate testing guidelines for fast-tracking these procedures for green building materials will be helpful.

Lastly, the solid-fuel pellets model evaluated in this study shows that despite good market feasibility, this segment is not picking up as a result of the following key challenges–

- Customisation required in different units, in particular, the grinding unit need specialised expertise in metallurgy. The learning curve for any start-up is therefore very high.
- The lack of backward linkages and the fluctuations in straw prices

Economic viability is excellent for both cases -

1. Industrial boilers (PBP= 1.8 years, NPV= INR 2.0 crore)
2. Thermal power plants (PBP=1.4 years, NPV= INR 2.9 crore)

Although the initial investment is the same for both use cases, a higher operating expenditure is required to produce SF pellets in the case of TPP. The analysis shows that the solid-fuel pellets model is most sensitive to straw prices fluctuation and becomes unviable beyond INR 2 per kg of rice straw. Also, it becomes unviable beyond a price point of INR 4.5/kg for SF pellets. This justifies the recent lifting of capping for SF pellets by NTPC at INR 5.5/ kg. Despite this, NTPC is not able to ensure the seamless supply of pellets. In light of these facts, locational criterion and competitive bidding need to be reconsidered for the SF pellet supply to thermal generators. It is worth noting that the SF pellet model in this study only evaluates the viability for supplying within a 150 km radius of the SF producing plant, whereas bids for supplying pellets invited by NTPC are for its plants across India.

A new policy mandate akin to the Government of India's fly ash directive could be issued for the use of straw-based SF pellets within a certain radius. NTPC has already set a precedent, but other private generators in the northwestern region and industrial boilers in Punjab and Haryana need to follow and start utilising pellets in small amounts of up to 10-15%.

Considering these insights and given the fact that necessary guidance has already been provided on this matter by concerned authorities and regulatory agencies (e.g. MoP, MNRE, CERC and CEA as discussed in Section 4.5); Government may consider mandating all such units to start consuming at least 5% rice straw-based SF pellets. Industrial boilers could be given a choice to co-fire SF pellets and rice straw directly as long as adequate emission control systems are in place and order.

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