Chapter 2

Mechanized Collection and Densification of Rice Straw

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Abstract The introduction of combine harvesters has made rice straw collection a major challenge and has brought bottlenecks to the rice straw supply chain. Due to this and the lack of knowledge on the straw's alternative uses, farmers burn the biomass in the field for ease of land preparation. This practice creates negative impacts on human health and the environment. However, as an alternative to burning, some Asian countries are developing increasing demands for rice straw for mushroom production, cattle feedstock, power generation, and building materials.

Mechanized straw collection has become necessary to increase capacity and to lower transportation costs. Baling machines can collect and compact rice straw in varying forms and densities. In the Mekong River Delta of Vietnam, adoption of rice straw balers have significantly improved rice straw management. A baler hauled by a 30-HP tractor has a collection capacity equal to five people, solving the labor shortage problem in rice straw collection. In addition, the volumetric weight of mechanically compacted straw bales is 50–100% higher than that of loose straw, which significantly reduces handling and transportation costs. High-density compaction (e.g., stationary compaction, briquetting, and pelletizing) can further increase the volumetric weight of baled straw from 400% to 700%, reducing transportation costs by more than 60%.

Mechanized rice straw collection and densification have contributed to improvement of the supply chain and resulted in sustainable management of rice straw. This chapter discusses the different technologies for rice straw collection, enumerating

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the benefits and downsides, as well as options for further densification to reduce transportation and handling costs. The benefits and costs of various alternatives for mechanized straw collection and densification are compared and further elaborated.

Keywords Mechanized straw collection · Rice straw balers · Densification · Straw compaction · Briquetting · Pelletizing

2.1 Introduction

The intensification of rice production and rising labor costs have led to the spread of combine harvesters in Asian rice fields at harvest time. Combine harvesters leave loose rice straw on the ground, making its collection and transportation difficult, laborious, and costly. Annually, about from 600 to 800 million tons of rice straw are produced in Asia; globally approximately 1 billion tons are produced (Sarkar and Aikat 2013; McLaughlin et al. 2016). Farmers choose the quick solution of burning rice straw to quickly remove the biomass and prepare the field for the next crop. In-field burning of rice straw contributes to the emission of greenhouse gas (GHG) and poses health and environmental hazards. In addition, the potential energy that can be derived from the biomass is lost (Tabil et al. 2011).

Loose rice straw is low in density, irregular in size and shape, and difficult to handle manually. Transportation and storage of rice straw in its original form are labor-intensive and costly. The amount of rice straw available for alternative uses would be limited if there is no better way to collect it after harvest. Collecting machines make it feasible to remove a huge amount of straw in a short time (between two cropping seasons): thus, they are more economical and efficient than manual collection.

Collection of rice straw in the field using balers is becoming common in many Asian countries such as China, India, Cambodia, Vietnam, the Philippines, and Thailand, partly due to environmental regulations against field burning due to its many harmful effects (see Chaps. 8, 9, and 10). Straw needs to be gathered from the field and compressed into bales to make it compact and easy to transport. Collecting dry rice straw (moisture content at 22–32% wet basis) during the dry season is easy with a baling machine because it is lighter and does not clog the machine during baling. On the other hand, working on a wet field is quite difficult and compressing wet straw is a big challenge for the baling mechanism and requires more energy.

High-density compaction of rice straw can produce high-end market products such as high-density square bales, briquettes, and pellets, the use of which can reduce handling and transportation costs and improve processing efficiency. (Adapa et al. 2011; Emami et al. 2014).

The densification of loose biomass, such as rice straw, provides several advantages such as (1) improved handling and conveyance efficiencies throughout the supply system and biorefinery in feed, (2) controlled particle size distribution for improved feedstock uniformity and density, (3) fractional structural components for improved compositional quality, and (4) conformance to predetermined conversion technology and supply system specifications (Tumuluru et al. 2010). The common methods used to achieve densification of loose biomass, such as rice straw, includes extrusion, compacting, briquetting, or pelletizing (Demirbas and Sahin-Demirbas 2009; Tumuluru et al. 2010).

2.2 Mechanized Collection of Rice Straw

Traditionally, rice straw left after harvesting is collected by hand or with tools such as a rake or makeshift stick and carried on a canvass (Fig. 2.1), in sacks or in a carrying mat to the areas where it will be used. This method is laborious and it takes a lot of time to finish collecting all of the straw scattered in a newly harvested area. With mechanized options such as a baler (Fig. 2.2), the process is more efficient, needing only one or two skilled people to operate the machine in the field to gather the loose straw.

Fig. 2.1 Manual method of collecting rice straw after harvest in Myanmar entails considerable manual labor

Fig. 2.2 Mechanized straw collection with a small tractor drawn round baler in Vietnam

2.3 Overview of Mechanized Straw Collection Technologies

Mechanized collection of straw scattered in the field involves three main operations: (1) picking up the straw from the field, (2) compressing it into bales, and (3) transporting the bales to the bunds. In some areas, there are also some machines that just pick up the straw in loose form and transport it to the side of the field for further densification and transport.

Rice straw balers can be classified according to their mobility, the technical operation of the compacting unit, the manner of straw collection in the field, and/or the bulk density of produced bales (Fig. 2.3). A mobile baler moves on the field to collect and compress straw into bales; it can be self-propelled or pulled by a tractor. A stationary baler, on the other hand, can be used to compress rice straw disposed by stationary threshers, which are still quite common in Asia.

Balers can also be classified according to compression density (high or low), shape of bales produced (round or square), and scale (large, at least with a 100-HP tractor or engine or small, with a less than a 60-HP engine). Figure 2.4 shows a schematic diagram of a round baler gathering rice straw, forming it into cylindrical bales, and expelling them onto the field. It is pulled by a tractor connected via three points with hydraulic ports to control pick-up height. It has a series of rollers that form the round bales. The pressure for baling is delivered through the tractor's power take-off (PTO) and the bale expeller consists of a built-in, independent hydraulic mechanism. It cannot work continuously as the operation must stop periodically so that the bales can be tied with a rope and then unloaded.

Fig. 2.3 Classification of mechanized rice straw collection in Asia

Fig. 2.4 Parts of a roller-type baler

Fig. 2.5 Square baler operating in the Philippines

Fig. 2.6 Schematic diagram of a square baler (top view)

Figures 2.5 and 2.6 show a square baler, which uses a piston mechanism to compress loose straw into square cubes. This type of baler can operate continuously in the field without needing to stop when bales are unloaded. The baler is connected to the tractor via a drawbar hitch with power for pickup and baling delivered through the PTO. The main components of this type of baler are: (1) a pick-up reel to collect scattered straw in the field, (2) a piston to compress the straw to a set density, (3) a knotter consisting of a needle and tying mechanism, (4) a bale-length controller, and (5) a bale-density adjuster. A flywheel minimizes load peaks on the PTO generated

by the reciprocal piston operation. In most models, a slip clutch on the flywheel protects the baler drive and packing system from overloading.

2.4 Commonly Used Rice Straw Balers in Asia

Small balers are better adopted and adapted in Asia as most rice fields are small at an average of about 0.05–0.4 ha (Gummert et al. 2019). Both round and square balers are adopted depending on many factors, such as soil and field conditions; preferences on bale weight; handling, transportation, storage, and multiple use purposes; and available tractors. For example, in Vietnam, farmers prefer small round balers because of their suitability for available tractors, speed in small fields, and the weight of the bales (12 kg bale^{-1}) produced is suitable for manual handling.

Self-propelled round balers were developed by some local manufacturers in Vietnam (Fig. 2.7a). The design is basically a round baler placed on a self-propelled undercarriage adapted from combine harvesters. It bales the straw, temporarily containing the bales on its carrier platform, and transports and discharges the bales onto the bunds. It requires a higher engine capacity compared to the tractor needed to pull the small round baler. Collection capacity is slightly lower as it moves on rubber tracks, which allow it to be used on wet fields. This and the machine's ability to move the bales to bunds have contributed to its wide adoption in the country.

Another type of self-propelled loose straw collection machine (Fig. 2.7b) was also developed based on the principle similar to the self-propelled baler except that it does not have a compacting component. This machine is used to gather scattered straw on the field and transport it loose to the side of the field.

Table 2.1 presents the features of some typical balers that are commonly used in Asia. The loose straw collection machine is normally used in a dry field for continuous operation, which is interrupted only when gathered straw is brought to the side of the field. A stationary baler can also run continuously and is typically used in a

Fig. 2.7 A self-propelled baler (a) and a loose straw collecting machine (b) operating in the field in Vietnam

Table 2.1 Typical straw balers used in Asia, working characteristics, and associated costs of collection

Collection machines	Examples of manufacturer	Types of movement	Working conditions and straw location	Weight of the bales at 14% MC (kg bale ⁻¹)	Engine power (HP)	Fuel consumption (L t ⁻¹)	Collection cost (US\$ t ⁻¹) ^a
Loose-straw collection machine with rubber tracks	Phan Tan	Powered by its own engine and transmission system, typically on rubber tracks	Both dry and wet fields; equipped with a loading platform for hauling loose straw to the side of the field	NA	50	3–4	12–15
Stationary baler	Locally fabricated	Hauled to baling location	Manual feeding of straw for stationary baling; needs 3–5 operators; bale dimension is 1.5 m wide × 2.5 m long	15–20	11–25	1–2	N/A
Self-propelled baler with rubber tracks	Phan Tan	Powered by its own engine and transmission system	Both dry and wet fields; equipped with a loading platform for hauling round straw bales to the side of the field.	13–15	45	3–4	16.4
Round baler	CLAAS; STAR; John Deere	Hauled by a 4WD tractor	Operates with rollers to form round bales that are left in the field	13–15 (small); 500–600 (big)	30–80	2–3 (small); 3–4 (big)	11.3–15.4 (small)
Square baler	CLAAS; New Holland	Hauled by a 4WD tractor	Uses piston to make bales and can move continuously without stopping for unloading bales; can bale 1.5–2 t h ⁻¹	15–20	50–60	3–4	12–15

Adapted from Nguyen-V-Hung et al. (2017)

^aCollection cost includes moving straw to the side of the field, US\$ t⁻¹

single location where loose straw is piled, e.g., it can be hauled, either by a two-wheel tractor or a pick-up truck, to where the stationary baler is located.

Round balers need to stop intermittently whenever bales are being discharged from the machines. Square balers, on the other hand, can be operated continuously in the field. Square bales are easy to pile and require much less space for storage than round bales. However, energy efficiency almost works out the same for both balers because a round baler has fewer power requirements than a square baler, which needs more power for compressing and baling. Round balers can also run much faster than square balers.

Rice Straw Collection in Thailand, China, and India

In Thailand, government prohibition of rice straw burning in fields has prompted farmers and the private sector to collect straw left in the field and sell it for alternative uses such as mulching and animal feedstock. The use of square balers to optimize the collection of the straw for biomass power generation has also become popular in Thailand. The cost of collection with square balers varies from US\$ 18–20 t⁻¹ for both of small and large square bales in Thailand (Delivand et al. 2011).

In China, the need for systems to collect, process, and transport rice straw encouraged the introduction of many types of balers. Small, round steel-roll balers are popular in the countryside, given their simple structure and low power requirements of about 13–20 kW (Wang et al. 2011).

In India, around 120,000 t of rice straw are collected annually to add 12 megawatts of electricity to the local power grid. The huge demand for rice straw requires larger balers, such as the widely used commercial CLAAS Markant 55 (Hegazy and Sandro 2016).

2.5 High-Density Straw Compacting, Briquetting, and Pelletizing

2.5.1 Compacting

Transporting bales after collection from the field has become feasible and costs less than transporting loose straw. However, for high-end markets, such as industrial cattle farms, large amounts of rice straw (e.g., more than 20,000 t for a cattle farm in Vietnam) must be transported long distances (sometimes more than 500 km) and stored for from 3 to 6 months. Round bales should be compacted into larger and higher-density square bales to reduce transportation and storage costs.

Compacting the bales utilizes technologies that apply high pressure, such as screw or piston presses. A few compacting machines that use the piston press are found in Asia. Two common variations are the vertical and horizontal compacting systems.

Fig. 2.8 Schematic diagram of a vertical bale compacting system

2.5.1.1 Vertical Compacting

Figure 2.8 shows a vertical compacting machine. The compacting process starts with loading straw bales into the compacting chamber through a belt conveyor. The piston vertically presses down on the bales in the chamber and then retracts before new bales are fed in. For each stroke, the piston presses three or four bales. At the end, the unloading chamber is opened to manually tie the compacted baled straws using nylon thread. After compaction, the square bales are unloaded using a forklift as shown in Fig. 2.9.

2.5.1.2 Horizontal Compacting

A schematic diagram of a horizontal compacting machine is shown in Fig. 2.10. Its mechanism is basically the same as the vertical system. The only difference is that it has a horizontal compressing direction. The main advantage is that the operation can be automated through conveyor belts instead of having an operator that is needed for the vertical compacting machine for loading and unloading. Additional advantages are consistent density of compacted materials and higher volume compared to vertical compactors (Fig. 2.11). On the other hand, vertical compactors use far less space and cost much less than horizontal ones.

Fig. 2.9 A vertical bale compacting system in operation

Fig. 2.10 Schematic diagram of horizontal compressing system

2.5.2 Briquetting

Briquettes (Fig. 2.12) are produced by compressing chopped straw into a cylindrical form through a briquetting press shown in Fig. 2.13. The hydraulic operation pressure of the briquetting press (Muetek MPP 130) is set to 15 MPa and the press works in three stages. First, the feedstock passes through the pre-compression unit, which presses it inside the pressing block in a Y-direction. When a resistance of

Fig. 2.11 Horizontal compressing system

Fig. 2.12 Rice straw
briquettes

8 MPa is achieved, the piston starts to operate and densifies the feedstock in an X-direction. At the open end of the pressing block, a pressing clamp is installed that opens to eject the produced briquette. The pressure at which the pressing clamp opens, which varies from 4 to 8 MPa, is related to the compaction density of the briquettes (Munder 2013).

Briquettes are also produced through: (1) the press-chamber principle, which consists of two parts: a heated die that acts as a press and a punch that fits in tight; (2) the screw principle, based on continuous extrusion of the feedstock by a screw through a heated tape die; and (3) a piston press, where a reciprocating ram presses the straw biomass in a die. The finished products would have varying energy density depending on the technology used (Munder 2013).

Fig. 2.13 Schematic diagram of the pressing unit

Fig. 2.14 Rice straw pellets

As fuel briquettes have an advantage over loose rice straw in terms of higher volumetric calorific value, improved combustion characteristics, ease of use when feeding the furnace, and uniformity in size and shape. A rice straw briquette has an average length of 10 mm (Munder 2013) and a density of up to 0.97 g cm^{-3} , which is 48 times the density of loose rice straw.

2.5.3 Pelletizing

Pellets (Fig. 2.14) are produced based on the principle of compressing ground straw. As shown in Fig. 2.15, the compression unit is composed of a horizontal or vertical ring die and rollers that put pressure on the inner surface of the ring die. During the pelletizing process, the ring die and rollers rotate and the raw materials fall in the

Fig. 2.15 Schematic diagram of ring die pelletizing Biomass pelletizing usually involves chopping, grinding, mixing, pelletizing, and packaging with the corresponding components shown in Figs. 2.16 and 2.17. Straw is chopped using a rotating chopper. Then, it is fed into a grinding machine. After passing through the grinding machine, the straw is collected using a cyclone and is temporarily stored in a silo. Finally, the ground straw is loaded into a pelletizing machine. Pellet quality is influenced by the characteristics of the feeding materials and operating conditions of the pelletizing process both of which are controllable (Rhen et al. 2005; Tumuluru 2014). Basic parameters that are necessary in the pressing process include a pressing pressure of 80 MPa and a temperature of 105 °C

clearance between the ring die and the roller, which are pressed into the holes on the ring die. Pellets are cut at the outer surface of the ring die and collected.

Compared with other compacting processes, such as briquetting and tumble agglomeration, pellets are generally regarded as the most durable because they are placed under the highest amount of pressure during formation (Whittaker and Shield 2017). Pelletizing can increase the bulk density of the biomass from an initial value of 40–200 kg m⁻³ to a final bulk density of 600–800 kg m⁻³. Pelletizing can overcome hurdles in cost and logistics in utilizing loose straw for energy or animal feedstock.

The product quality and calorific value of straw to be pelletized can be improved by mixing it with various additives, such as starch, molasses, ash, montan resin, paraffin, palmitin, and anthracite and lignite coal. The compressing pressure is the most significant factor affecting pellet density and the biomass type significantly affects pellet durability (Adapa et al. 2011). The physical quality of compacted loose biomass materials is partly indicated by compressive strengths, durability, stability, and smoothness (Demirbas and Sahin-Demirbas 2009). The specific energy requirements of different types of biomass for compression vary according to the compressed density of materials and the moisture content of biomass inputs. Density is identified as an important parameter in compression, i.e., the higher the density, the higher the energy/volume ratio.

Fig. 2.16 Schematic diagram of pelletizing system. (Adapted from Nguyen-Van-Hieu et al. 2018)

Fig. 2.17 A rice husk pelletizing machine. (Adapted for pelletizing rice straw)

Pelletized rice straw can be used as fuel, animal feedstock, or material for anaerobic digestion. The pelletizer die hole size is known to have an important effect on the moisture content of the pellet, while the temperature reached during pelletization can also influence pellet quality.

Straw densification through pelletizing can increase bulk density from 600 to 800 kg m⁻³ (Kaliyan and Morey 2009; Kargbo et al. 2009). The average specific mass of a straw pellet may also reach 1244 kg m⁻³, which is higher by 1000% compared with loose straw. Said et al. (2015) reported that the ideal value for high-quality pellets is 1200 kg m⁻³. Pelletized rice straw has an advantage of preventing straw materials from floating in water when using the straw for other processes such as anaerobic digestion. The use of enriched pellets as feed for cows results in minimal waste and leftovers during feeding.

The production costs of rice straw pellets are computed based on the estimated cost of equipment and assumed cost of straw and labor at the locality (including depreciation, material, and labor costs). In one case study in Vietnam (Nguyen-Van-Hieu et al. 2018), materials (straw and cattle feed additives) cost US\$ 280 t⁻¹; straw prices ranged from US\$ 90 to 100 t⁻¹; and depreciation, labor, and electricity costs were estimated based on the existing rice husk pelletizing system. Given a pelletizing cost of US\$ 22.6 t⁻¹, straw pellets cost approximately US\$ 125 t⁻¹. Pelletizing can significantly reduce transportation costs. In the same case study, a cubic bale was sold at a price of US\$ 110 t⁻¹ excluding transportation cost, which was about US\$ 35.5 t⁻¹ for a distance of 1000 km by truck. The cost of grinding straw was estimated at US\$ 100 t⁻¹. Transporting pelletized straw was found to be more economical and practical compared to bales.

2.6 Conclusions and Recommendations

Alongside the spread of combine harvesters, government regulations against open field burning of rice straw, and increasing use of straw, mechanized collection is gaining ground in Asia. Small balers with a capacity of 1–2 t h⁻¹, which are easy to maneuver in small fields, have been found suitable in Cambodia, the Philippines, and Vietnam. The self-propelled baler—a successful innovation in Vietnam—is being adapted in Southeast Asian countries, such as Cambodia and the Philippines, because it reduces labor requirements in hauling baled straw from the field to the bund. Another advantage is the machine's rubber chain-wheel mechanism, which makes it suitable for use in wet fields, particularly in areas where field drainage is a problem.

A case study in Vietnam showed that mechanized collection can reduce costs by about 68% compared to manual collection. As labor scarcity rises, machines become a more sustainable option for Asian rice fields where farmers have traditionally resorted burning straw after harvest, which is easier and cheaper.

As Asian countries move towards field consolidation and upgrading of contractual arrangements among farmers, mechanized collection is likely to become more

efficient. Further research has to be conducted to understand field efficiency vis-à-vis field capacity so that (1) the use of baler machines is optimized, (2) the sustainability of custom servicing business models is assured; and (3) machine owners are adequately informed on the viability of their investments.

Rice straw densification—through compacting, briquetting, or pelletizing—results in better handling and storage of the byproduct, which, in turn, reduces transportation costs and makes efficient use of storage facilities. The technologies now available, such as briquette presses and pelletizers, also provide options for other uses of rice straw, such as animal feed, fuel, and feedstock for energy generation.

The processing of loose straw into pellets can further save transportation costs and improve logistical processes as experienced in Vietnam. Research is still required to improve the quality of densified straw, either for animal feed or fuel. Researchers should look into locally available binding materials that are cheap and of high quality to improve pellet and briquette properties in terms of strength, durability, density, nutrition (for animal feed), and calorific value (for fuel).

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