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MECHANIZATION & POSTHARVEST MANAGEMENT

to Support Sustainable and Low Carbon Rice Production

Mechanization and Postharvest Management to Support Sustainable and Low Carbon Rice Production

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1. Overview of challenges and solutions

Rice production in Asia and Africa has faced labor shortages and climate change issues such as unanticipated droughts and floods, causing unstable yields and a high risk of crop losses. In addition, low farming efficiency, high carbon footprint, and high postharvest losses are the major constraints in rice production. Low farming efficiency (high energy and labor cost and agronomic input use) is mainly caused by poor land consolidation, lack of precision land leveling, crop establishment, and crop care. These inefficient practices and poor water and rice straw management cause a high carbon footprint. Furthermore, poor harvest and postharvest management also cause high postharvest losses (more than 10%) and significantly contribute to rice carbon footprint. This document introduces several mechanization and postharvest solutions to address the said challenges and problems, which have been developed by IRRI and country partners.

i) Mechanization: Laser land leveling and mechanized crop establishment help to significantly increase agronomic use efficiency (Figure 1). The application of LLL in combination with precision sowing and nutrient management in rice production has improved farmers' net income from the reduced seed rate, irrigation water, agronomic inputs, pest and desease risks, lodging and postharvest losses.

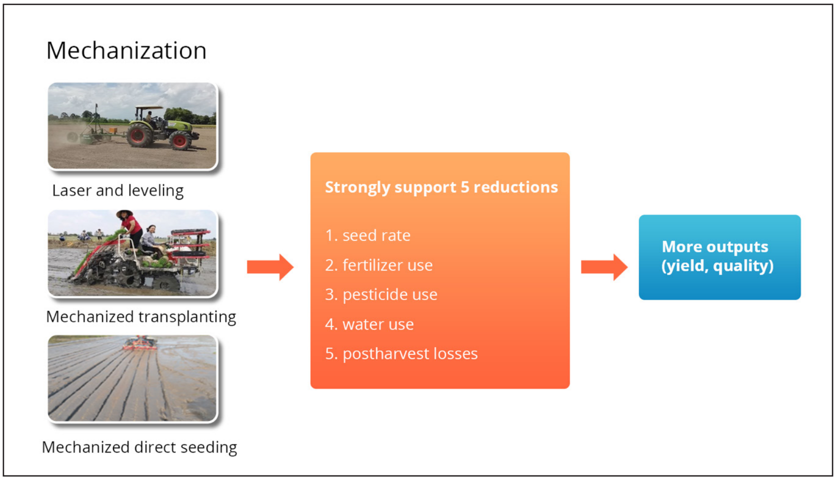

Figure 1. Mechanization for increased farming efficiency and low carbon rice production

ii) Best postharvest management: optimized harvesting timing and technology, paddy logistics, drying, storage, and milling management help to significantly reduce postharvest losses and maximum maintain grain quality. Some good practices widely used for rice postharvest handling and processing are shown in Figure 2.

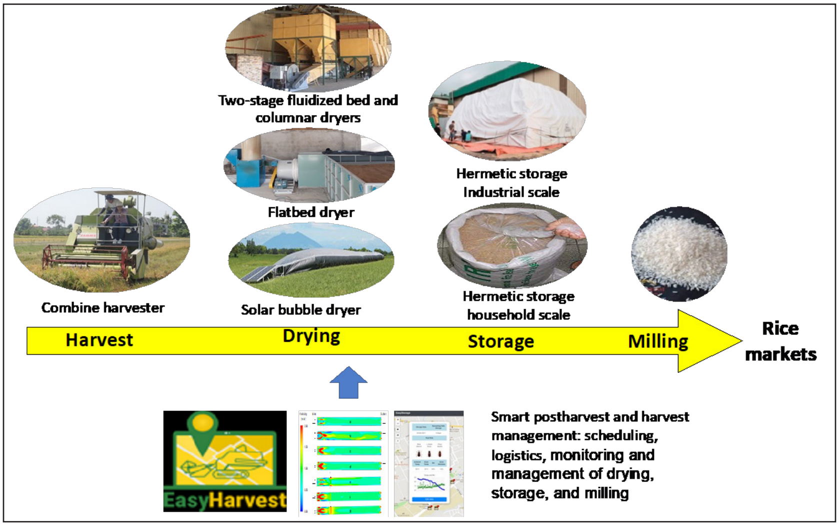

Figure 2. Postharvest solutions to support sustainable and low carbon rice value chains

iii) Rice straw – based circular economy: this solution converts by-products or wastes to co-products or inputs in the bio-circular that helps to reduce environmental footprint and enable sustainable and organic farming. The rice straw-based circular economy includes the major technologies and practices such as rice straw balers, smart logistics, productions of mushroom, cattle feed, bio-fertilizer, bio-plastics, and urban agriculture (Figure 3). Removal of rice straw from the field for the said productions will eneable to qualify the susatainbel rice straw management requirement of the sustainable rice production standard (SRP) and significantly reduce carbon footprint in low land rice production. In addition, organic fertilizer produced from rice straw will enable a major input for organic farming.

Figure 3. Sustainable rice straw value chain and circular economy

2. Mechanization

2.1. Laser land leveling

Small-sized and uneven fields can cause poor management and low efficiency of agronomic inputs. It can also hamper mechanization and cause lodging of rice plants and nonuniform paddy at the maturity stage leading to high postharvest losses (Figure 4).

Figure 4. Poor field leveling can cause difficulty in crop establishment (left) and crop lodging at maturity (right)

For example, assuming a small and a large field with the same slope, the larger dimension can lead to higher unevenness (Figure 5) resulting in more difficult management of water, fertilizer, pesticide, and lodging.

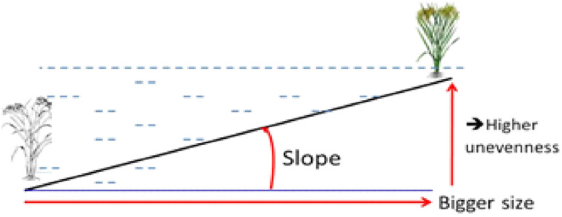

Figure 5. Slope and plot size diagram

Laser land leveling (LLL) is used for precision land reformation in rice cultivation to optimize water and crop management. LLL increases yield and input-use efficiency of water, energy, and agronomic inputs. A laser-controlled leveling system, as shown in Figure 6, involves a soil-moving scraper bucket (sometimes called a drag bucket) attached to a 4-wheel tractor. A laser transmitter unit with a rotating laser transmitter placed at the side of the field creates a horizontal laser plane of light above the field (Figure 7). A laser receiver mounted on the scraper bucket measures the height of the scraper bucket relative to the laser plane of light and, through some electronic and hydraulic controls, adjusts the height of the scraper bucket according to the signals received. The mechanism keeps the scraper bucket always at the same height, resulting in the soil being scraped off and collected from the elevated areas of a field and getting dropped in the low areas. Compared to farmer practice or conventional soil-moving equipment, LLL enables extremely accurate leveling of fields under dry conditions.

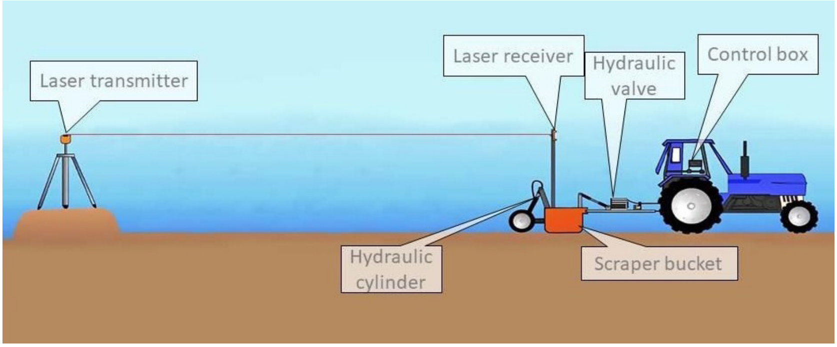

Figure 6. Components of a laser-controlled land leveling system. Adapted from IRRI YouTube Channel (2012)

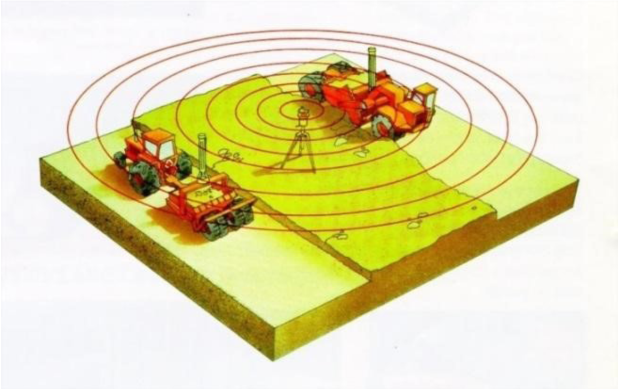

Figure 7. LLL with stationary transmitter on a tripod creating a laser plane of light and two machines with receivers in the field. Source: RKB (2013)

Benefits of laser land leveling

LLL technology can reduce the unevenness of the field surface to 1–2 cm height difference, even in a large field of 3 ha; in this case the field slope for draining the field can be set to 0.02%. Application of this technology can lead to an increase of land use efficiency by 3-6% when consolidating several small fields into one large field; savings of irrigation water by 20–40%; increases in fertilizer and pesticide-use efficiencies by 10–13%; and yield increases in rice by 10–13%.

The usual practice in Southeast Asian countries (SEA) is that LLL is applied with a 5-year cycle to reform the field in dry soil conditions to have higher input-use efficiency. Benefits of LLL are affected by many factors such as soil conditions, equipment quality, operation of the technology, etc. LLL can reduce carbon footprint (GHG balance for all inputs and outputs) by at least 10% in rice production. Furthermore, LLL application enables farmers to enlarge field size by consolidating small fields into larger ones, and this allows the mechanization of rice production, leading to other benefits such as better crop stand and pest management, solving labor shortages, and increasing productivity, efficiency, and effectiveness.

On the other hand, there are challenges in promoting LLL such as high cost and lack of service availability, lack of scale-appropriate technology adoption interventions, etc. LLL can be more effective if integrated with other supporting technologies such as drones for field topographic surveys and optimized scheduling of service providers, such as using EasyHarvest (https://easyharvest.irri.org).

2.2. Mechanized crop establishment

Scale-appropriate and site-specific precision sowing options, including mechanized direct seeding and mechanized transplanting, can help increase seeding precision, vigor of seedlings, and yield. These practices also reduce seed rate, fertilizer and pesticide use, water use, and carbon footprint compared with broadcast-seeding practices such as manual broadcast, blower, and drone seeding.

2.2.1. Mechanized transplanting

Transplanting of rice is a process of transplanting young rice seedlings either manually or using a machine. Manual transplanting is a traditional practice that requires about 100–200 labor-hours per ha and almost the same amount of labor for producing seedlings. Moving from manual to mechanized transplanting has been happening in the MRD, particularly for seed production, due to its advantages of increased yield, reduced risks of pest and diseases, reduced postharvest losses, and better conditions for roguing in seed production. Mechanized transplanting employs two separate operations that are seedling production and transplanting (Figure 8).

Figure 8a. Seedling production

Figure 8b. Mechanized transplanting

Compared to the broadcast seeding method, transplanting has the following advantages:

- Reduced seed rates (40–60%): A lower seed rate is achieved with transplanted rice as it can be properly controlled and managed during the raising of seedlings in the nursery, and through regular spacing of seedlings when transplanted.
- Lower risk of seeds being eaten in the field by birds and rats.
- Better weed control: Rice seedlings have a head start compared to the weeds in the field so weeds will be lesser of a problem. This is further supported by proper levelling of the land. When the field is well-leveled, weeds can easily be controlled with better water management.
- Allows deeper anchoring of roots into the soil, thus lodging is less likely throughout the growth of the crop and this leads to a postharvest loss reduction of about 5–10%.
- Roguing in seed production is easier in transplanted rice.

When labor is limiting and expensive, using machines for transplanting is more advantageous. Around 20–30 persons are needed for the manual transplanting of rice to cover 1 ha/day as compared to mechanical transplanting which would only need two or three operators to accomplish transplanting 1–2 ha/day. The advantages that can be derived from the use of a mechanical transplanter in establishing rice in the field are:

- Efficient use of resources by saving labor costs,
- Timely transplanting of seedlings at optimal age,
- Reduced transplanting shock,
- Ensured uniform spacing and optimum plant density (26–28 hills/m2)
- Higher yield compared to traditional method (e.g., manual broadcasting),
- Lower drudgery and health risks for farm laborers, and
- Improved employment and entrepreneurship opportunities for rural youth and women through custom service provision.

Seedling production

One of the important requirements for raising seedlings for the mechanical transplanter is proper preparation of the growing medium. Providing a good growth medium for healthy seeds would ensure healthy and vigorous germination and growth. There are materials that are needed for preparing the growing medium – soil sieve and mixer, soil with a pH of 4.5–5.5, coconut sawdust, rice husk ash, and NPK fertilizer. Soil pH can be tested either with the use of a pH meter or litmus paper. Soil to be used can be sourced directly from the rice field or from the uplands. Dry the soil properly when obtained from the rice field. Grind the soil into finer particles and allow it to pass thru a 4x4-mm sieve to remove larger particles and impurities that could hinder good growth and development of seeds and disturbances during the process in the transplanting machine. Prepare a good mixture of soil, coconut coir, or rice husk ash and fertilizer by adding 25 g of crushed fertilizer to 1 kg of soil into a mechanical mixer with 70 L of soil, then add 30 L of coconut coir or rice husk ash and mix them evenly by running the machine for at least 5 minutes. The fertilizer material should be mixed evenly into the growing medium to ensure uniform growth of the seedlings.

The soil obtained from the uplands (with pH of 4.5–5.5) that is prepared according to the recommended best practice above would result in good development of seedlings that are strong, large, and with high resistance to pests and diseases. Taking soil from riverbeds for use as a growing medium is not recommended due to its high pH and potential contamination with toxic substances that could result in weak seedlings with small and sickly stems and leaves. The use of garden soil alone as a growing medium is also not good for the development of strong and highly resistant seedlings because of its high pH, impurities, and poor nutritional value of the soil. A study conducted by E-Rabbani et al. (2017) demonstrated that seedling preparation using a polythene mat with mud soil from the rice field is less laborious and not so time consuming and results in a well-developed root system as compared with using crushed soil on a plastic tray.

The well-prepared growth medium is then evenly scattered on seedling trays either by hand or using a spreader machine, which guarantees evenly scattering of properly selected good-quality seeds. The mixed medium should be 2 cm thick and, for this, about 2.5 L are needed to be evenly distributed in the seedling trays. The soil in the tray must be thoroughly moist, which can be achieved by sprinkling about 1–1.5 L/tray before seeding. Avoid scouring the surface of the mixed medium on the tray when applying water to ensure uniform seedling growth. Uniformly scatter on the tray about 200 g of pre-germinated seeds and cover it with soil. Provide adequate moisture on the growing seedlings by spraying about 1-1.5 L of water per tray in the morning (from 8:00 to 10:00 am), especially when the weather is very hot.

A well-developed seedling mat on the tray could easily be pulled out and should not break when rolled. The seedlings (Figure 9) are ready for transplanting after 10–20 days in the nursery when three leaves are already visible and stem height is from 13 to 17 cm. Before planting, water the seed bed and pay attention that no water drops from the seedlings when they are taken out from the seedling tray. When the seedling is too dry, the sliding movement on the transplanting machine could be hindered, which causes unplanted spots on the field, while a seedling mat that is too wet will become loose and may cause the seedlings to float.

Figure 9a. Rice seedlings

Figure 9b. Seedlings ready for transplanting

Figure 10 show the two types of seedling machines widely used in the MRD, the Kubota Srk-800 and the SYS-800C, respectively. Both machines have an average capacity of 800 seedling trays/hour, which provides enough seedlings to transplant 0.5 ha.

Figure 10a. Seedling machine Kubota Srk-800

Figure 10b. Seedling machine SYS-800C

Typical models of mechanical rice transplanters

Table 1 shows the main features and specifications of the mechanical transplanters widely used in MRD. The walk-behind transplanter (Figure 11a) is used in some regions with small fields while the self-propelled transplanters (Figures 11b and c) are commonly used for seed production in MRD.

Table 1. Specifications of mechanical transplanters widely used in MRD.

Parameters/ features	**Transplanters**		
	Kubota SPW48C	**Yanmar VP7D25**	**Kubota NSPU68C**
Operational type	Walk-behind	Self-propelled	Self-propelled
Number of rows	4	7	6
Planting distance	Row spacing (cm): 30		
Hill spacing (cm): 12, 14, 16, 18	Row spacing (cm): 25		
Hill spacing (cm): 10, 12, 14, 16, 18, 22	Row spacing (cm) 30		
Hill spacing (cm): 12, 14, 16, 18, 21			
Machine size (length x width x height in cm)	214 x163 x 91	328 x 210 x 188	300 x 221 x257
Weight (kg)	160	784	590
Engine power (fuel)	Gasoline 4.24 HP	Diesel 17.4 HP	Gasoline 17 HP
Transplanting capacity (ha/hr)	0.07–0.15	0.2–0.4	0.2–0.4
Fuel consumption (L/ha)	5–8	7–12	7–12

Figure 11a. Walk-behind transplanter Kubota SPW48C

Figure 11b. Kubota NSPU68C transplanter

Figure 11c. Yanmar VP7D25 transplanter

2.2.2. Mechanized direct seeding

Direct seeded rice (DSR), especially wet seeding, is a common practice in Asian countries as a response to labor-, water-, and energy-intensive problems. Of which, manual broadcast seeding and blower seeding are widely adopted. These broadcast seeding practices use a high seed rate, usually higher than 150 kg/ha due to its non-uniform seeding. Therefore, mechanized direct seeding (mDSR) for more precise seeding has been promoted to address the problems of broadcast seeding.

There are two main types of mDSR including dry- and wet-seeding. Dry-mDSR is mostly a matured technology and recently adopted in several countries such as India, China, etc.. Responding to the demand and in alignment with the development, mDSR has been also currently introduced and tested in some SEA countries such as Cambodia and the Philippines. Some typical mDSR machines are shown in Figure 12.

Figure 12a. mDSR in India (source: Bhullar et al., 2022)

Figure 12b. mDSR tested in Cambodia (source: Martin and Flor, 2022)

Figure 12c. mDSR tested in the Philippines (source: Bautista, 2022)

On the other hand, wet-mDSR is still at the adaptation stage, particularly for the high demand for wet irrigated rice in MRD of Vietnam and Cambodia. The major challenges for this practice are: (1) it requires a well-leveled field and land preparation; (2) and the risk of seeding losses caused by unpredicted rain. Some typical wet-mDSR machines that have been tested in MRD of Vietnam are shown in Figs. 13.

Figure 13. Typical wet-mDSR machines being tested in MRD

2.2.3. Agronomic requirements for mechanized crop establishment

Seeds quality is very important to ensure healthy and vigorous seedlings to be transplanted by a mechanical transplanter in the field. Inbred seed of about 25–50 kg/ha is needed with a germination rate of at least 85%. Seeds must be treated to avoid diseases that could affect the robust establishment of the crop in the field. Seed treatment with fungicides is necessary to prevent the vulnerability of seeds from fungal infection.

The seeds are grown in a nursery in the same manner as for manual transplanting. Seeds must be soaked in clean water for 24 hours and this water must be cleaned every 5–6 hours if the water used is not flowing. After soaking, the seeds are drained of water and incubated for 24 hours until the swollen embryos appear on the seeds or when the germ sprouted by 0.5–1.0 mm is already visible (Figure 14a). Seedlings can be raised on the plastic seedling trays that are usually included with the mechanical transplanting machine or by implementing a mat-type nursery without the need for the plastic trays. A good mixture of soil media for the seedling tray and mat nursery would ensure good germination of seeds. The seeds can be raised on the seedling trays or mat nursery for about 12–18 days.

Soil, moisture content, and compaction

The optimum field condition for mechanical transplanting is achieved with thorough land preparation. After land preparation, the field must be soaked with standing water of about 2–3 cm and afterwards allowed to drain naturally. A water depth of about 1–2 cm is suitable for the mechanical transplanter.

The soft mud layer in the field should be not more than 25 cm. This can be gauged by walking on the field to check how deep your feet get immersed. Too deep mud in the field will prevent efficient operation of the transplanting machine because of wheel slippage and possible sinking of the machine and this will result in many seedlings sown near the spot where the wheels slip.

The field must be plowed evenly to ensure appropriate hardness. Puddle the soil evenly to avoid soil clumps, residues, and soil blocks. Over puddling the soil must be avoided as this will affect the efficiency of field operations. The degree to which the soil is puddled is related to the hardness of the soil surface. A soil that is too hard will cause the seedlings to float and fall on the ground and too soft soil will result in a disorder in planting and soil material will get into the machine, which might cause it to get stuck in the field. The suitable hardness of the soil can be ascertained by dropping a golf ball on the field from a height of 1 m. If the golf ball barely is submerged on the surface, then the soil surface has adequate hardness (Figure 14b).

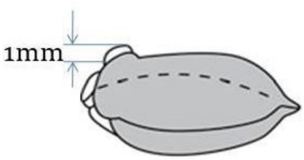

Figure 14a. Seed with sprouted germ ready for seeding

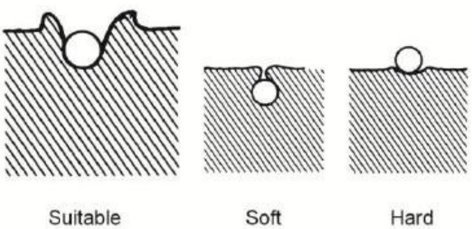

Figure 14b. Using a golf ball dropped from 1 m to indicate soil compaction and hardness

Land preparation

A thorough land preparation with good field leveling is a must for mechanical transplanting. This will ensure uniform crop establishment through a nourishing soil-seedling environment due to even distribution of agronomic inputs and irrigation on the soil surface that prevents invasion of weed population. This is achieved by allowing enough time of about 3–4 weeks before planting to ensure complete decomposition of leftover plant residues from previous cropping. The field for mechanical transplanting should undergo a thorough land preparation to destroy breeding places of insects and their larvae underneath the soil and incorporate crop residues. The requirements for a good land preparation should include the following operations:

- *Primary tillage* – This is the initial cutting of the soil with the use of a plow (e.g., disk (Figure 15a), chisel, moldboard) to a deep of about 10–15 cm that is done after harvest. Plowing of the paddy field should not be deeper than 25 cm.
- *Secondary tillage* – This is done 1 week after primary tillage to further break the soil clods and incorporate biomass thoroughly into the soil with the use of any of the following implements – rotovator, spike tooth harrow, and disk harrow (Figure 15b). The depth of the cut should be about 5–7.5 cm, which is shallower than the primary tillage. This operation could be done 1–3 times until the desired soil clod is achieved.

Field leveling comes after the tillage operations and is a must. A well-leveled field improves crop establishment of mechanically transplanted rice resulting in a better crop and uniform maturity. The even distribution of agronomic inputs and irrigation water is guaranteed in a well-leveled field. The implementation of laser-controlled land leveling would result in a precisely leveled field. This can be done once every 5 years and in dry field conditions. Succeeding leveling in the successive seasons of growing rice, before laser leveling needs to be reapplied, could be done with the use of a harrow, rotovator or a tractor fitted with cage wheels with a leveling plank being pulled behind (Figure 15c) on a puddled field. The field must be puddled (not compacted) by applying water during the secondary tillage operation, which helps facilitate faster decomposition of crop residue. A well puddled field ensures a good soil environment for deeper root growth of the seedlings. The field must be irrigated at least 12 hours before mechanical transplanting and the amount of water in the field must be maintained at 1–2 cm during the transplanting operation.

Figure 15a. Disk plowing

Figure 15b. Harrowing

Figure 15c. Puddling and wet-leveling using a tractor with cage-wheel

After completing the tillage and leveling operations, make sure to repair the bunds and ditches. The functionality of well-maintained bunds ensures lower incidence of pests such as rodents and prevention of irrigation seepage. The bunds should be constructed around the field at a height and width of not greater than 30 cm and should be properly sealed and compacted. A well-maintained ditch around the field also ensures even distribution of irrigation water (irrigation ditch), eliminates toxic substances from the field (drainage ditch), and allows the plants to produce deeper and stronger root system.

2.2.4. Summary of the advantages of the mechanized crop establishment compared with broadcast seeding

Mechanized direct seeding

Advantages (compared to the broadcast seeding and mechanized transplanting)

- Reduced seed rate by 2-3 times compared with broadcast seeding
- Seeding cost = 1/3-1/2 of mechanized transplanting
- Reducing fertilizer use by 20-30% and reducing the risk of pest/ diseases
- No yield penalty
- Reduced postharvest losses by reducing risks of lodging and increased grain quality and uniformity
- Less water use than transplanting (for seedlings)
- Less GHG emission

Disadvantages (compared to mechanized transplanting)

- Still need to use herbicide for weeding (before seeding)

Mechanized transplanting

Advantages (compared to the broadcast seeding and mechanized direct seeding)

- Roguing in seed production is easier in transplanted rice.
- Reduced seed rates by 2-3 times compared with broadcast seeding
- Reducing fertilizer use by 20-30% and reducing risk of pest/ diseases
- No yield penalty
- Reduced postharvest losses by reducing risks of lodging and increased grain quality and uniformity
- Lower risk of seeds being eaten in the field by birds and rats.
- Better weed control: can apply water-stagnant to control weed after transplanting, so there is no need for herbicide application.

Disadvantages (compared to mechanized transplanting)

- High crop establishment cost (for seedling and transplanting, about 250 $US/ha), double than that of mechanized direct seeding
- More water used for seedling

3. Harvest and postharvest management

Rice post-production processes, which involve all practices from harvesting to milling, are estimated to incur losses of 10-40%. Of these processes, harvesting and drying are the major causes of both physical and quality losses. Poor harvest management, such as early or late harvest, manual harvesting, etc. causes postharvest losses more than 5% (both quality and quantity). Sun drying losses average 2–5% and are mostly caused by improper handling and poor conditions. In addition, both physical and quality losses can be severe due to delays poor logistics that delay drying, which are the major challenges in most of the Southeast Asian Countries such as Cambodia, Thailand, and Vietnam. A delay of harvesting leads to overmature rice grains causing high shattering loss of more than 5%. Delays to wet paddy drying of more than 24 hours lead to significant quality losses of up to 1%/day from discoloration, mold, and broken grains. This document introduces some good technologies and practices currently developed or promoted by IRRI and some country papertners.

3.1. Harvesting

Harvesting is the process of collecting the mature rice crop from the field. Harvesting of paddy includes cutting, stacking, handling, threshing, cleaning, and hauling. The goal of all harvesting systems is to maximize grain yield and to minimize grain damage and quality loss. Harvesting can be done manually using sickles and knives, or mechanically with the use of threshers or combine harvesters. Regardless of the method, basic guidelines should be followed that will ensure that grain quality is maintained during harvest operations and harvest losses are kept to a minimum.

3.1.1. Timing of harvesting

The timing of harvest is important to reduce losses in both quantity and quality. Grain losses in the field may occur from shattering, lodging, and pests such as birds, rodents, and insects. Premature or early harvesting will result in a higher percentage of unfilled or immature grains, which reduces the overall yield, increases grain breakage during milling and has a negative effect on seed quality. Late harvesting will result in increased physical losses in the field due to shattering, lodging, and birds and may decrease quality through weathering in the field and grain breakages at the mill. Timing of harvesting can also affect the germination potential of rice seed. There are several different ways to determine whether the crop is ready for harvest. These include:

- Number of ripe grains per panicle: The crop should be cut when 80–85% of the grains are straw- or yellow-colored.
- Grain moisture: The grain moisture content for harvesting is best between 22 and 24%. If the crop is too dry, higher shattering losses will occur and cracks or fissures may develop in the kernels. If the grain is too wet, it is more difficult to remove from the panicle and losses may occur during threshing. Farmers often determine the harvest timing by biting the grain. Grains should be firm but not brittle when squeezed between the teeth. However, large variations in moisture estimation can occur using this method
- Number of days after sowing: Generally, early duration varieties are ready for harvest 100–120 days after establishment, medium duration varieties between 120–140 days after establishment and long duration 140–160 days. Transplanted crops will mature faster in the field than direct seeded crops.
- Number of days after panicle initiation and flowering: The time taken from panicle initiation to ripening is similar for most rice crops. Optimum time of harvest is 55–60 days after panicle initiation or 30 days after flowering.
- Harvest management: The time of cutting must be closely linked with threshing and drying capabilities. Threshing and drying should be done within 24 hours of cutting. If cut panicles are left in stacks for more than 24 hours, the grain will begin to heat up and discolor and increase the risk of mold growth and losses to pests such as birds and rodents.

3.1.2. Harvesting options

There are two practices commonly used for rice harvesting in South Asia (SA) and Southeast Asia (SEA): (1) manual cutting and mechanical threshing; and (2) combine harvesters. The first one causes higher grain losses because of the delay of harvesting and transportation of rice plants between cutting and threshing. Therefore, the second practice, combine harvesting, was rapidly adopted in SA and SEA as a response to the demand and address the said constraints of the first practice. A combine harvester combines crop cutting, threshing, and cleaning into a one-pass operation (Figure 16). Grain is temporarily stored on board the combine before discharge into a bulk wagon or into bags. Straw is discharged behind or to one side of the combine into a windrow. Some combines also have straw choppers and devices to spread the straw evenly. Proper use of combine harvesters can help to significantly reduce harvesting and postharvest losses from avoiding the transportation losses between different stages of cutting and threshing and delay of harvesting.

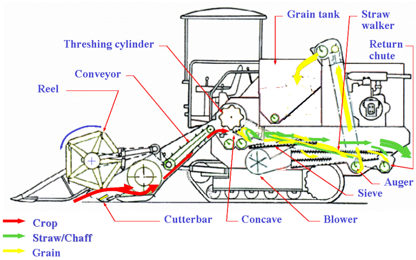

Figure 16a. Schematic diagram of the Crop Tiger with tangential-axial flow threshing unit (Source: CLAAS)

Figure 16b. A combine harvester operating in Vietnam

3.2. Drying and storage

Drying is the process of reducing grain moisture content. Drying is the most critical operation after harvesting and delays in drying or incomplete drying will reduce grain quality (quality loss) and quantity (physical loss). Drying and storage should be considered as related processes and, in some instances, can be combined as one with in-store drying. Storage of high moisture grain will reduce quality, irrespective of the storage facility.

Drying should begin as soon as possible after harvesting as even short-term storage of high moisture grain can cause quality deterioration. Ideally drying should commence within 12-24hrs after harvesting. Table 2 shows the recommended moisture content for storage of paddy grain and seed along with the potential problems when the moisture content exceeds these limits.

Table 2. Moisture contents required for safe storage for different storage periods.

Storage period	Required MC for safe storage	Potential problems
Weeks to few months' storage	14% or less	Molds, discoloration, respiration loss, insect damage
8 to 12 months	13% or less	Insect damage
More than 1 year	9 % or less	Loss of viability

Problems encountered in high-moisture grain

Grain is hygroscopic and the final moisture content depends on the relative humidity of the air that surrounds it. This means that, when grain is in contact with high humidity air, moisture content increases. This is a major problem in tropical areas during the rainy season when the relative humidity may reach 95–100%. Grains and seeds stored in tropical climates face to the following problems:

Heat: When wet grain is stored in sacks or in bulk, the grain will heat up through natural respiration. Grain temperatures between 25 and 40°C provide excellent growth conditions for molds and insects.

Molds: The growth of molds can propagate diseases and may release toxins into the grain. Although some molds may be present in the grain at harvest time, proper drying and storage systems will prevent further multiplication of these molds.

Insects: Insect infestation is always a problem in stored grain even when the grain is completely dried. However, lower moisture and lower temperatures will help reduce insect problems. At temperatures below 13°C, all insects become inactive.

Discoloration/yellowing: Grain discoloration is closely linked to heat build-up in the paddy grain after cutting. Discolored grain reduces the market value of rice as whiteness and translucency is important quality characteristic for rice consumers.

Loss of germination and vigor: Higher moisture grain respires at a faster rate, which reduces germination and seedling vigor. The increase in molds and seedborne diseases also reduces germination.

Loss of freshness/odor development: Rice stored for longer periods at high moisture and high temperature will develop unpleasant odors, which reduces its market value.

Reduced head-rice yield: A major cause of fissuring of rice kernels is rewetting or reabsorption of moisture by dry grain. This occurs when wet grain is mixed with dry grain and when dry grain is exposed to air with high relative humidity. Fissures in the grains lead to breaking during milling and reduce the head-rice recovery.

Within this document, we introduced several typical drying and storage technologies and good practices for paddy grains promoted by IRRI. The detailed information are described in the "Further readings" section.

Common practices of paddy drying can be classified into two main categories that are sun-drying and mechanical drying (Figure 17). Solar dryers which usually consist of mechanical blowers are considered as mechanical dryers.

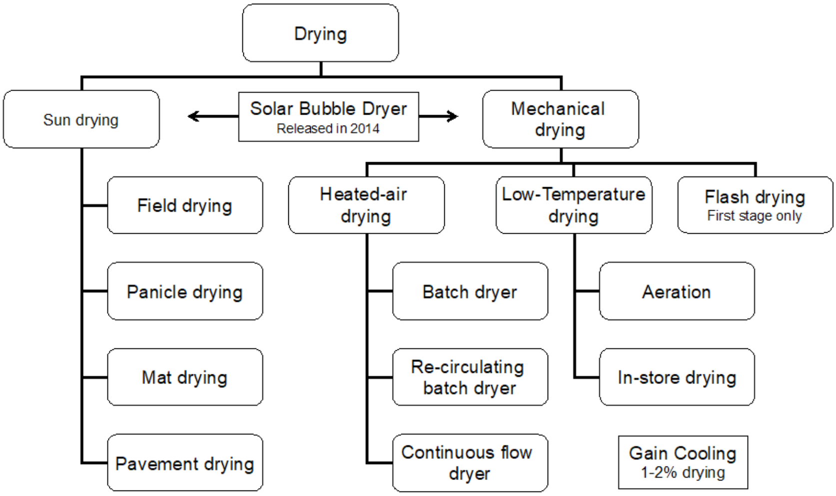

Figure 17. Classification of rice drying methods and technologies

3.2.1. Solar bubble dryer (SBD)

The solar bubble dryer (Figure 18a), using only solar energy, was developed by IRRI, the University of Hohenheim, and GrainPro Inc.. This dryer has a capacity of 1-ton paddy grains and/batch with the drying time about 16 hours for the SEA climate. The SBD was also further developed by IRRI for mushroom drying (Figure 18b).

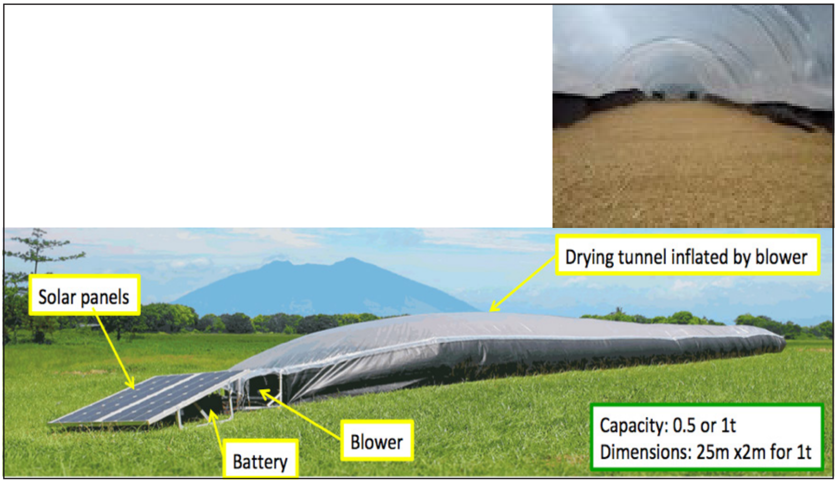

Figure 18a. Solar Bubble Dryer for paddy grain drying

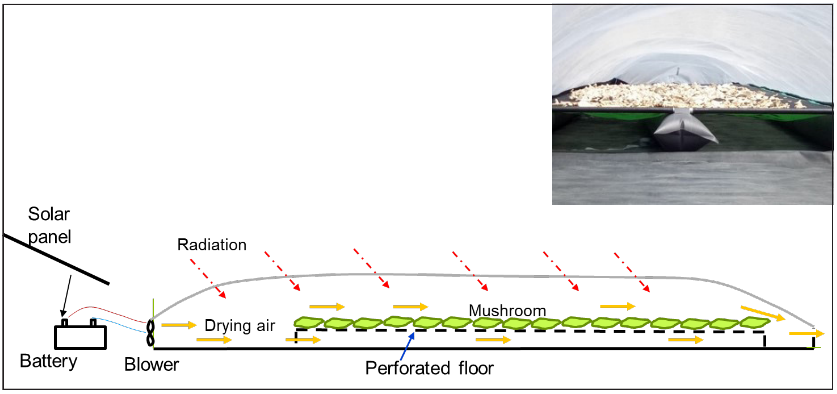

Figure 18b. Solar Bubble Dryer for mushroom drying

3.2.2. Flatbed dryers

Flatbed drying technology for paddy drying is widely used in SEA because of its advantages such as low drying cost and suitability for both small and industrial scales. Drying cost accounted for the machine depreciation, maintenance, labor, and energy is about 6-12 $US per ton of paddy grains dried. A FBD consists of three main components including blower, furnace, and drying chamber (Figure 19a). Grain is placed in a rectangular bed on a perforated false floor. The furnace heats ambient air, which is sucked by a fan and pushed through the grain mass until it exits from the grain mass surface. The drying process continues until the grain mass is dried to the desired moisture content, usually 14%. A FBD with the drying air moving in one direction (usually upwards) is called conventional flatbed dryer (FBDc), while that with drying air moving in two directions, upward and downward, is called reversible airflow flatbed dryer (FBDr) (Figure 19b). Drying material is loaded into the drying bin with a depth of 25–40 cm and 50–60 cm on a perforated floor for the FBDc and FBDr, respectively. Drying air temperatures are in the range of 42–45^{o}C for grain and 40–43^{o}C for seed production, respectively.

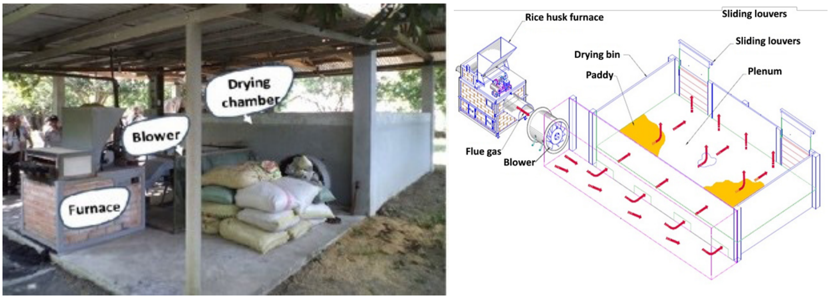

Figure 19a. Flatbed dryer used for paddy grain drying

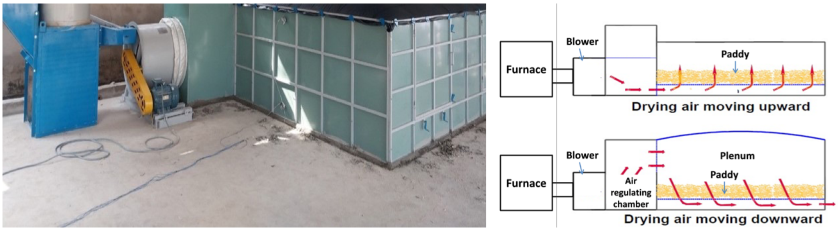

Figure 19b. Reversible air flatbed dryer

3.2.3. Two-stage drying for industrial scale

A two-stage drying system, including a fluidized-bed and recirculating columnar dryers (Figure 20), is suitable for industrial scale as its advantages of high capacity and mechanized and automatic operations. Wet paddy grains are dried by fluidized-bed dryers at the first stage, usually to reduce 2-4% of grain moisture content (MC), and then dried until qualified MC for storage (usually 14%) at the second stage. Typically, a two-stage drying system with a fluidized-bed and ten recirculating columnar dryers has a capacity of 300 tonnes per working day (about 8 hours). Its drying cost in SEA is about 5-10 $US per ton of paddy grains dried.

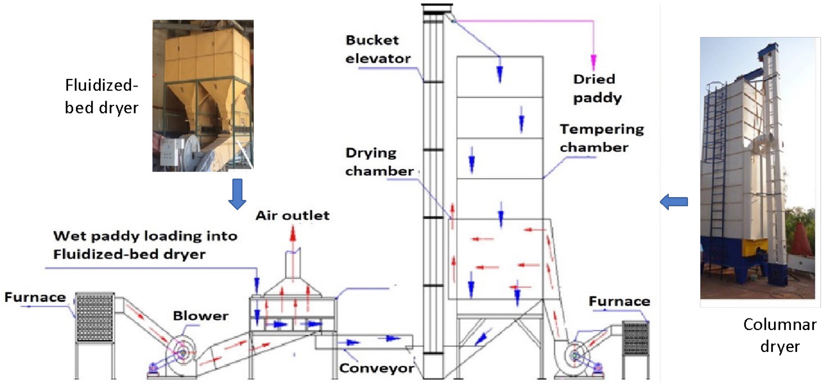

Figure 20. Two-stage drying system
(adapted from Nguyen-Van-Hung et al., 2018)

3.2.4. Hermetic-sealed storage

Sealed- or hermetic-storage systems are a very effective means of controlling grain MC and insect activity for grain stored in tropical regions. By placing an airtight barrier between the grain and the outside atmosphere, the MC of the stored grain will remain the same as when the storage was sealed. Respiration by the grain and insects reduce the oxygen level and increase CO2, which kills the insects. Hermetic systems can increase head rice by 10% and double the viability of seeds.

Sealed storage containers come in all shapes and sizes (Figure 21). They may range from a small plastic container to the more complex and costly sealed plastic commercial storage units with 1t -1,000-ton capacity per unit. Hermetic Super bags with 50 kg capacity are now also commercially available and widely used.

Figure 21. The hermetic IRRI Super bag for 50 kg (left), hermetic Cocoon™ with 5-t capacity (center), and hermetic Cocoon 300-t capacity (right).

3.3. EasyHarvest for smart harvest and postharvest management

The inappropriate use of machines and poor scheduling of harvesting operations among service providers could reduce if not eliminate the potential benefits of mechanization. In the rice processing industry, poor management of postharvest machines also leads to high losses, low efficiency and effectiveness, and high cost. The inefficient management system is hampered by the following constraints:

- Lack of information on machine availability and poor coordination between service providers and farmers
- Poor matching of field conditions with types of machinery resulting in low field operation efficiency and high losses
- Lack of anticipation of the demand for services and poor management resulting in poor planning for the contractors, low machinery utilization rates, thus low effectiveness
- Inefficient use of machinery leads to an increase in GHG emission
- Postharvest losses also lead to carbon footprint, up to 30% of that of the whole rice value chain

EasyHarvest, developed by IRRI, is a digital tool available as an Android mobile application providing smart links between the farmers and machinery service providers (Figure 22). It is designed to optimize the scheduling of combine harvester services corresponding to the actual needs of farmers and the availability of the combine harvesters. EasyHarvest uses algorithms that consider field conditions, anticipated harvesting dates, and available infrastructures. As with most data-driven tools, EasyHarvest becomes "smarter" as more data parameters are used.

EasyHarvest has been tested for the "machine search and scheduling" for laser land leveling and rice straw balers in the Philippines in 2020. It was then developed and tested for wet paddy logistics with a function as Uber-boat in MRD of Vietnam in 2021-2022 (Figure 23). As of April 2022, EasyHarvest has the following core components:

- Access to real-time geo-location of machines and equipment (e.g. combine harvesters, laser land leveling, rice straw balers, paddy transporting boats, etc.) via GPS devices.
- Smart wet paddy logistics based on real-time information matching between the fields, boat services and the rice mills; and the paddy parameters on the transporting boats such as loading, dates, grain temperature, locations, etc.
- Smart paddy storage, informing the safe storage time based on the real-time environmental and grain parameters.
- Access to a database containing field conditions of registered farmers' fields, including location and harvesting-related parameters
- A self-service data management dashboard that can be accessed by account holders to manage their fields or machinery
- Two machinery scheduling options: a self-service booking of machinery done by the field owner and a resource-optimization option tailored to larger scales, wherein both field and machine resources are managed by a single entity, making harvesters –field matching fully automated.
- An interface that can include other data sources on precision farming and digital agriculture, especially on the environmental impact of straw burning, nutrient management, and other digital platforms for agriculture.

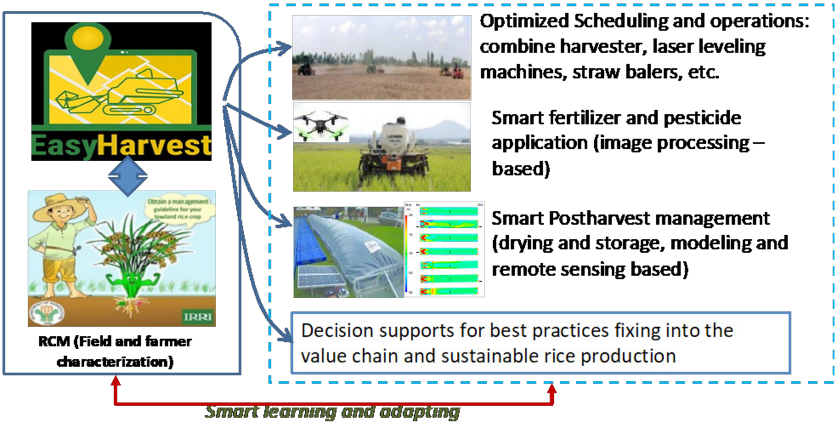

Figure 22. Integration in and major functions of EasyHarvest

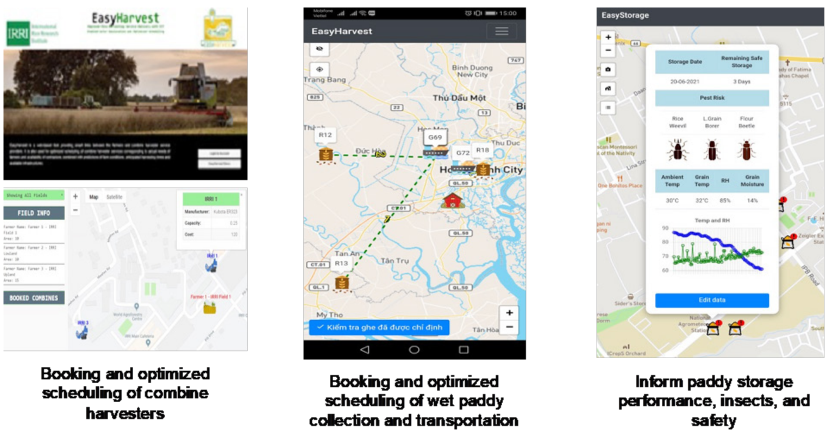

Figure 23. The modules of EasyHarvest being tested

4. Sustainable rice straw management and bio-circular economy

Managing rice straw remains a challenge which globally produces about 500 million tonnes of rice and the same amount of rice straw each year. Labor shortage for straw collection, the low economic value of rice straw, and lack of economically viable knowledge lead to the predominant practice of straw burning. In-field burning of rice straw results in biodiversity loss, soil nutrient loss, and human health problems.

Rice straw-based circular economy (RiceEco) developed by IRRI and the country partners is a solution can help to avoid pollutions from birning, increase rice income and decreased carbon footprint. RiceEco includes the major technologies and practices such as rice straw balers, smart logistics, productions of mushroom, cattle feed, bio-fertilizer, bio-plastics, and urban agriculture. Removal of rice straw from the field for the said productions will eneable to qualify the susatainbel rice straw management requirement of the sustainable rice production standard (SRP) and significantly reduce carbon footprint in low land rice production. In addition, organic fertilizer produced from rice straw will enable a major input for organic farming.

4.1. Mechanized collection of rice straw

The enormous amount of rice straw being scattered in the field after combine harvesting prodded the necessity of using mechanical straw collection such as straw baler for easy removal in the field with increased capacity and lower transportation costs. Rice straw balers can effectively collect and compact loose straw in the field for easy hauling to the side of the field and storage areas for further use. Time is efficiently managed and utilized when rice straw balers are employed to remove scattered rice straws in the field as compared to manual collection which would need around 3 person-days per hectare. Traditional collection of rice straw in of field labor. Collection of rice straw with the use of straw balers eases the task and lessens the time consumed to complete it. Generally, there are two main classifications of balers: stationary and mobile balers. As the name implies, stationary baler is not mobile but conducts baling of straw in one place and straw is being fed into the machine, while a mobile baler moves around the field to collect straw to be baled. A mobile baler is further classified into two, which are: (1) a round baler which compresses collected loose straw inside the chamber with a series of rollers to form cylindrical bales that stops intermittently during disposal (Figure 24); and (2) a square baler can compress the straw inside the chamber continuously and dispense the compacted straw in the field without stoppage of the operation (Figure 25).

There are three main operations involved in rice straw baling depending on the type of balers – (1) picking of loose straw in the field; (2) compaction of the straw by the baling machine; and (3) disposal of compacted or baled straw in the field and/ or conveyance to the side of the field.

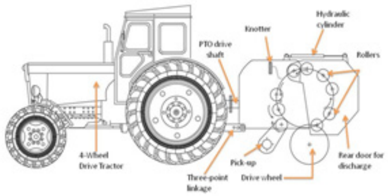

Figure 24a. Schematic diagram of a round baler.

Figure 24b. A round baler in field action.

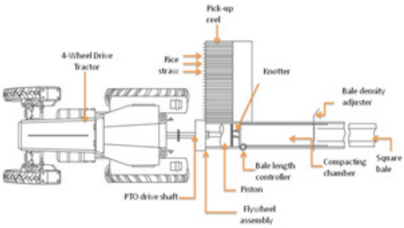

Fig 25a. Schematic diagram of square baler.

Figure 25b. Square baler operating in the field.

There are some adaptations of rice straw balers that can be found in Asia in varying capacities and sizes. In Vietnam for example, the small round bale has been fitted with a hauling platform that enables collection to be done continuously while baled straws are being loaded onto the platform (26). This type of baler is also called a self-propelled baler because it can be operated even without the use of tractors to haul it in the field. Another kind of self-propelled mechanized straw collection is a loose straw collecting machine. These self-propelled rice straw collection machines are adapted from combine harvesters; the rubber tracks designed for mobility allows operation in both dry and wet field conditions. The field capacity, however, is lower compared to balers that are pulled by a 4WD tractor.

Figure 26. Self-propelled round baler (left) and loose straw collecting machine (right).

4.2. Rice straw based mushroom production

The species of rice-straw mushrooms, Volvariella volvacea, is commonly used because of it grows easily and has a short growth duration of 14 days. The species grows in tropical weather at around 30-35°C for the mycelia development stage, and at around 28-30°C for the fruiting body production stage. The main inputs for mushroom growing are rice straw, spawn, labor, and water. The mushroom harvest usually starts during the third week after inoculation and ends 1 week later. Outdoor mushroom production (Figure 27a) is a common practice in Vietnam's Mekong River Delta (MRD). The low investment cost is an advantage of this income-generating enterprise. It produces a yield of 0.8 kg of mushrooms per 10 kg of dried straw and generates a net profit of USD 50-100 t-1 of straw. Indoor mushroom production (Figure 27b) is a less common practice because of higher investment costs and the necessary strict control of the growing conditions. On the other hand, indoor mushroom growing produces about a 2-kg higher yield per 10 kg of dried straw.

Figure 27. Mushroom production in Vietnam, a-outdoor, b-indoor

4.3. Rice-straw silage for cattle feed

Rice straw is of poor quality to serve as a livestock feed. It has a low C:N ratio and high NDF and ADF, which affects its nutritive value. Nevertheless, it is considered as a potential feed additive for increasing the energy and protein content. The prescribed consumption limit of rice straw by ruminants is 1.0 to 1.5 kg per 100 kg live-weight per day. Urea treatment of straw, such as a technology developed by a collaboration between the Philippine Carabao Center and IRRI (Figure 28), which is rice straw ensilaged with 2–4% urea can improve consumption and digestibility of the rice straw as fodder.

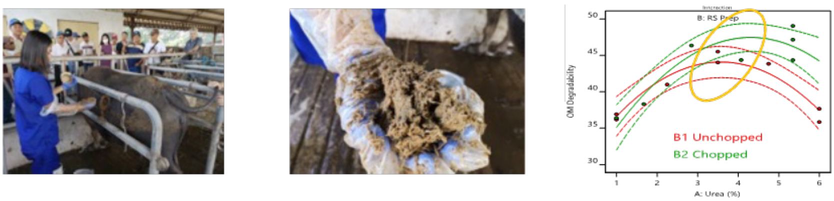

Figure 28. optimization of rice straw pretreatments for ruminant feed (IRRI Rice-StrawPH project, 2020)

4.4. Mechanized rice straw composting

Composting is a process to convert organic mass, such as rice straw, other agricultural by-products, digestive, animal wastes, etc., into a more decomposed product. The compost product can be used as soil amendment or fertilizer. For organic rice production using rice straw compost replacing chemical N, one ha of rice production needs about 6-10 tons of compost produced from the same amount of rice straw mixed with 20-40% of animal manure to have an optimized C/N ratio of 25/1. In addition to the generation of value from rice straw, rice straw composting demonstrated a significant reduction of GHG emissions when compared with incorporation of raw rice straw. Furthermore, avoiding rice straw burning is also one of the criteria to qualify under the global Sustainable Rice Platform Standard leading to an increase in income from rice

Mechanized rice straw composting (Figure 27), developed under an IRRI-led project, is an innovation that combines physical and bio-chemical processes for optimizing rice straw decomposition efficiency and organic fertilizer quality. This technology was verified in Vietnam with the following features:

- Hauled by a 30-35 HP tractor.
- Capacity: 25-30 tons/hour per each pass of turning
- Fuel consumption: 0.1 -0.15 l diesel per ton of compost

The technology with the composting process shown in Figure 29 enable to optimize and efficiently stimulate response of affected parameters such as C/N ratio, temperature, moisture content, pH, bio-activeness, anaerobic and aerobic conditions. Rice straw composting using this technology takes about 45 days, about half the time of traditional practices such as manual composting and bulldozer-mixing.

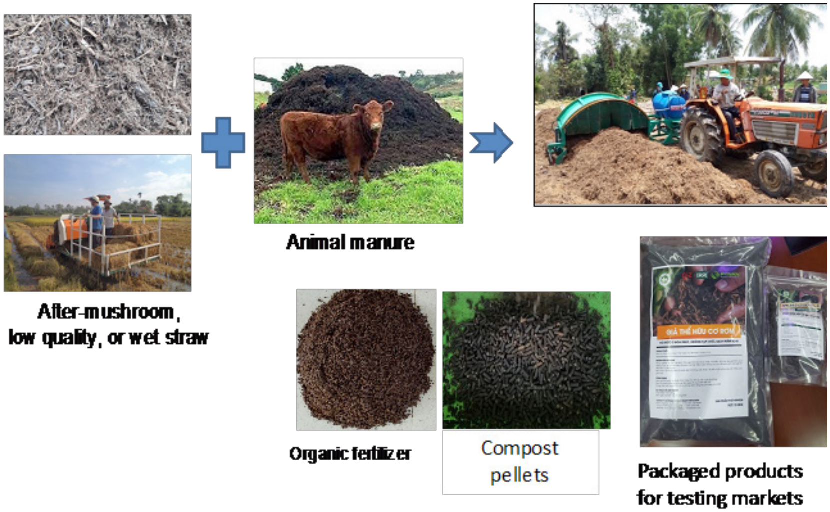

Figure 29. Mechanized rice straw composting.

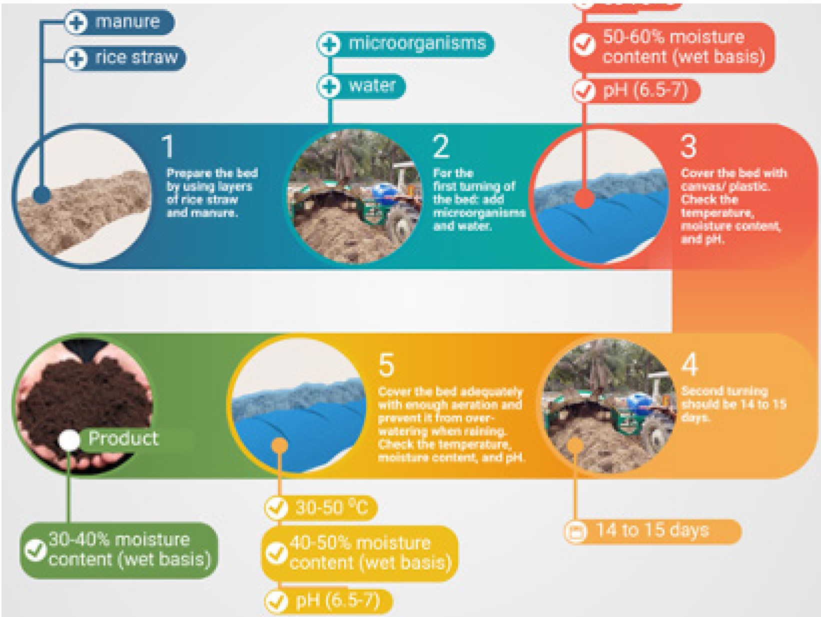

Figure 30. Step-by-step mechanized rice straw composting

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