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REVIEW ARTICLE

# Advancements in rice harvest machinery towards enhanced efficiency in modern agriculture

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**Abstract**

Rice is a vital food crop globally, ensuring food and nutritional security for the population. Same way, rice is an important food crop in the India and also has many traditional values. The mechanization of rice cultivation has significantly advanced, covering various aspects of farming operations, including transplanting, weeding, spraying, harvesting and post-harvest processes. The majority of rice harvesting operations worldwide are mechanized, marking a major leap in agricultural technology. Numerous studies and research initiatives have contributed to this transformation, delivering innovative technologies and methods that have made rice harvest mechanization a successful strategy. However, despite these advancements, several constraints and challenges persist in rice harvest mechanization. This paper delves into the influence of the crop harvesting stage on grain losses, examining how factors like crop moisture content and timing affect efficiency. Additionally, it reviews different mechanical harvesting mechanisms, exploring their working principles, advantages and disadvantages. By consolidating insights from extensive research, the paper provides a comprehensive overview of rice mechanization, emphasizing its significance in improving productivity while reducing labour dependency and drudgery. Concluding with an analysis of existing constraints, the paper highlights the scope for further improvements in technology to make harvest mechanization more accessible and efficient for rice farmers.

**Keywords:** combine harvester; harvesting efficiency; reaper; rice mechanization

## Introduction

Globally, many countries have agrarian economies in which rice is the dominant crop. It is the second most important cereal crop that feeds more than 50 % of the world population (1, 2). By 2050, global population is projected to reach 9.7 billion and more than half of the projected increase will be concentrated in just nine countries, the maximum being in India (3). Globally, numerous varieties of rice have been developed and released by several organizations such as International Rice Research Institute (IRRI), Philippines. India has released 1200 varieties of rice, Japan cultivates 150 varieties and the National Crop Gene Bank in the Chinese Academy of Agricultural Sciences (CAAS) has conserved 64,269 acessions of rice germplasm. To meet the food demands of such a growing population, production must also increase, which in turn needs a complete successful mechanization. educe the drudgery, especially on women labourers, who are the predominantly engaged gender in harvesting at many regions, requires suitable machines and tools for harvest. Ensuring timely harvest (Table 1) is a key factor in increasing higher productivity. Numerous research exists on physiological workload andergonomic study of women on rice harvest. Hence there was a development of ergonomically designed tools/machines for rice harvesting from manually operated to power-operated. The designs of these rice harvesting machine is focused on durability, reliability, simplicity and ease of maintenance. Moreover, farmers usually recover both grains and straw from rice crops, as the cost of straw accounts for- 15 –20 % of that of the grain from the same region. Proper crop stage for harvesting, choosing the right harvesting machine and mechanism and optimizing the harvester parameters can improve the harvesting efficiency.

Given the importance on paddy harvest mechanization, this review article was planned to provide a comprehensive analysis of paddy harvest mechanization, covering the past, current and future prospects. Discussions were made on the limitations and research gaps of the current scenario. This article was aimed to serve as a valuable resource for researchers, policymakers and practitioners working towards sustainable and efficient paddy harvesting solutions.

**Table 1.** Harvest time and its results at different location.

| S.No | Harvest Time | Result | Location | Reference |
|---|---|---|---|---|
| 1 | 30 Days after 50% flowering | Reduced post-harvest losses | Iran | Firousi *et al.,* 2013 |
| 2 | 30 to 35 days after flowering | Higher head rice yield | Bangladesh | Hossain *et al.,* 2009 |
| 3 | 36 - 39 days after flowering at 20 - 30% moisture content | High total milled and head rice recovery | Pakistan | Ali *et al.,* 1993 |
| 4 | Too early at high moisture | susceptible to mold growth, insect Infestation and high amount of broken seeds, also increased the drying cost | | Khan, 2010 |
| 5 | 5-, 7- and 10-days delayed harvest | 3, 6 and 11 % decrease in yield | | Simon& Duff (1973) |

## Suitable Crop Stage for Harvesting

The crucial and influential processes that impact the quantity, quality, losses and cost economics of cereal crops are harvesting and threshing. The effect of harvest time on milling quality of rice is significant and optimum harvest time varies across different rice varieties (4). To minimize field losses due to overripening, shattering and unfavourable weather, farmers of Southern and South-eastern Asian regions usually harvest the crop at maturity (5). At both early and late maturity stages, head rice recovery was observed to be low. Researchers have also reported that by the application of Artificial Neural Networking (ANN), the harvesting stage can be determined and the post-harvest losses can be minimized by analyzing both machine and crop parameters (6).

## Levels of Harvest mechanization

Manual tools (sickles), animal-operated devices (reapers) and power-operated machines (reaper and combine harvesters) fuelled by petrol, diesel, etc., represents different stages in the mechanization of rice harvesting. Each level is discussed as follows.

## Harvest mechanism

Agricultural harvesting employs different cutting mechanisms depending on crop type, field conditions and machine design. Shear cutting mechanism is the most common method used in sickles and reapers whereas impact cutting is employed in flail-type harvesters, while spinning disc cutting units operates based on tearing action etc. Each method is optimized for specific crops to ensure efficient and minimal loss harvesting. For efficient paddy harvesting, low energy cutting methods are employ-yed to minimize crop damage and ensure a clean, uniform harvest across different field conditions.

Manual harvesting was done using shear action. Different harvesting methods are discussed in the follow-ing sections. In manual cutting, a curved blade is drawn across the stems, applying both shear and frictional forces to achieve a clean cut.

The cutting mechanism in paddy harvest machines involves a moving blade (knife section) and a stationary surface (ledger plate or guard fingers), which work together to create a shearing force that slices through crop stems.

### Manual harvesting

Manual harvesting requires150-200 man-hours per acre and is mostly carried out by sickles (Fig. 1). These sickles are based on the principle of cutting (shear and friction) as explained previously. Two major categories of sickles are, serrated (depth of about 1 mm) and plain (non-serrated type). The productivity of serrated sickles is reported to be higher than the non-serrated sickles (7). Improved sickles have been developed by Gujarat Agricultural University, Central Institute of Agricultural Engineering (Naveen Sickle), Dr. Bala Sahab Konkan Krishi Vidyapeeth - Dapoli (Vaibhav). The performance of Naveen and Vaibhav sickles were evaluated in comparison with the local sickle for Rice harvesting with twelve farm women in Madhya Pradesh (8). The mean heart rates during the operation of these sickles were 103 beats $min^{-1}$, 107 beats $min^{-1}$ and 106 beats $min^{-1}$, respectively. The workload was under an acceptable limit for a day-long work with normal rest pauses. The output of local (65.4 $m^2$ $h^{-1}$) and Vaibhav sickles (60.7 $m^2$ $h^{-1}$) was significantly higher than that of the Naveen sickle (47.3 $m^2$ $h^{-1}$). Consequently, a sickle named Bokaro refined sickle was developed in Jharkhand (9) and was compared with different types of sickles involving farm women (Fig. 1). The study concluded that the newly developed sickle is comparatively the most suitable for farm women, being cost-effective, operationally efficient and helpful in reducing drudgery. Specifications of these sickles are presented in the Table 2.


**Fig. 1.** Different types of sickles (9).

Sickles are developed in various designs based on the crop type, harvesting conditions, regional preferences and ergonomic factors. For example, long-handled- serrated sickles are employed for faster harvesting, lightweight sickles to minimize hand fatigue and sturdier sickles for use in rough terrain. Different sickle types are designed to optimize harvesting efficiency, reduce labor fatigue and meet specific crop and regional requirements. Farmers choose sickles based on their comfort, cutting speed and the type of crops they harvest.

### Reapers

A reaper is a farm implement or person that reaps (cuts) crops at harvest when they are ripe. Reapers are typically employed to harvest crops such as cereal grass. The first documented reaping machine was the Gallic Reaper which was used in the modern-day France during Roman times (10).

There are several forms of developments in reapers, which are powered by engines (self-propelled), tractor, power tiller, animals and human labor. The main components of

**Table 2.** Specification of different types of sickles (9).

| Name of the Sickle | Material (Blade) | Total weight (gm) | Length of curvature of blade (cm) | Width of curvature of the blade (cm) | Diagonal distance (cm) | Material (Handle) |
|---|---|---|---|---|---|---|
| Local | Iron/ Mild steel | 165 | 15 | 11 | 14 | Iron/Mild steel |
| Vaibhav | High Carbon Steel | 172 | 21 | 15 | 20 | Plastic |
| Naveen | High Carbon Steel | 240 | 22 | 12 | 20 | Wooden |
| Refined | High Carbon Steel | 220 | 21 | 15 | 20 | Wooden |

these developed reapers comprise of bar assembly, crop dividers, star wheels, conveying belts, etc with size (width) varying from 0.7 to 2.5 m (1, 1.2, 1.6, 1.8, 2.2 m), but only a few are in practical use.

Animal drawn reapers: Animal-drawn reapers are typically operated using a pair of bullocks. The components of these reapers include a knife bar, ground wheel which employs a gear box, crank, connecting rod mechanism, etc. As the machine is pulled forward by the bullocks, a reciprocating motion is imparted to the knife bar with a peak cutting velocity (100 m min$^{-1}$). Cutting occurs due to the shearing action of the knife bar.

In India, Punjab Agricultural University, Ludhiana, developed an animal-operated reaper during 1964, that was operated with more than one pair of bullocks. Subsequently, an engine was added in a modified design to enable operation with a single pair of bullocks. However, the windrowing quality was not observed to be good. In continuation, several other institutions in New Delhi, Pant Nagar and Bhopal carried out several research on the same machine. Similarly, a single-wheeled single animal operated reaper was developed in Austria and animal-operated reapers along with conventional cutter bars and reels were designed in China (11). With further inventions to reduce drudgery, power-operated machines had evolved over time.

Power operated reapers: The first power-operated Vertical Conveyor Reaper (VCR) was designed in China during 1976. Later, IRRI, Philippines collaborated with China (Chinese Academy of Agricultural Mechanization Sciences) and India (Central Institute of Agricultural Engineering, Coimbatore) to develop a power-operated VCR (12). Subsequently, based on the local cultivation practices and ergonomic aspects, many researchers across various parts of the globe modified and developed power-operated reapers.

Due to the inherent shortcomings like non-suitability to taller crops and drudgery in the IRRI design reaper, the same was modified to increase its applicability and utility (13). Based on specific requirements, modifications such as power cut-off mechanism for harvesting unit, a reverse gear facility, re-sizing to match the prime mover, reducing width of steel wheels with provision for attaching rubber tire wheels were developed.

In most of the power reapers, the cutting width was typically 1.2 m. A self-propelled reaper which is powered by a diesel engine was subsequently developed by Bangladesh Agricultural University (BAU), (14). This reaper was later modified to enhance its field performance. Iron cage wheels were replaced with pneumatic lugged wheels for better traction and less slippage. For increasing the cutter bar speed, the original 102 mm cutter bar pulley was replaced with a 114 mm diameter pulley. The idler pulley provided improved belt tension, ensuring proper power transmission (15).

The components of power-operated reaper are shown in Fig. 2 It consists of lugged wheels, a cutter bar, crop row dividers, conveyor belts, star wheels, operator's controls and a traction frame. The engine powers the cutter bar and conveyor belts. As the machine moves forward, the crop row dividers direct the plant towards the cutter bar, facilitating the shearing of crop stems. The cut crop is windrowed by the conveyor belt and is bundled manually before proceeding with threshing.

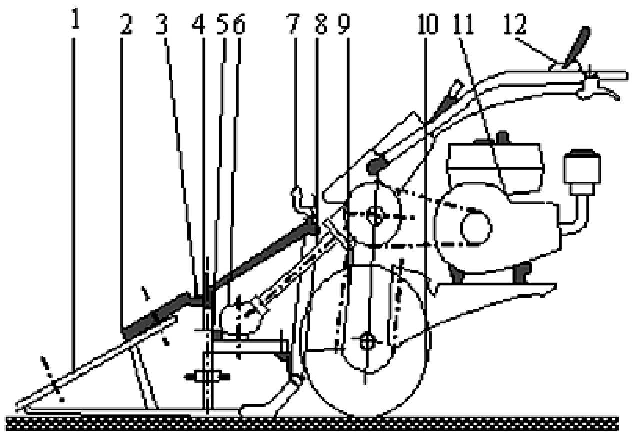
Recently there have been a growing interest in electric powered reapers, which operate through battery systems. Such reapers might reduce the ergonomic issues associated with the engine powered models, thereby improving operator's comfort. Solar-powered harvesters remain uncommon, as solar energy in agriculture is still an emerging sector. However, efforts have been made in the development of a hand-held solar powered cutter (12 V, 24W) for rice harvesting (2).

Kirloskar, Shrachi Agrimech, Greaves, Vardhman, Kerala Agro Machinery Corporation Ltd (KAMCO), Krishi-tech are some of the manufacturers of power-operated reapers.

## Power tiller-operated reapers

Developments of power tiller-operated reapers were begun in the 1970s featuring a reel, cutter bar, swath divider, engine, etc. These types of reapers have limited applicability in India due to restricted use of power tillers across the country (13).

Moreover, the power requirement and power availability of walking type tractors (tillers) does not align with the requirements of the common cutting widths, rendering these power tillers unsuitable for reaping operations. However, power tiller-based combine harvesting is under investigation at research and development sectors of premier institutes and industry.




(1) Drive rubber belt (2) Big belt pulley (3) Upper carrier chain (4) Lower carrier chain (5) Driving carrier chain (6) Reaping gear box (7) Elevating mechanism (8) Universal drive shaft (9) Main gear box (10) Tyre (11) Diesel engine (12) Controls

**Fig. 2.** Construction of power reaper (16).

## Tractor operated reapers

Tractor-operated reapers are further classified into front and side-mounted types, powered by Power take-off. Among these, the front mounted Vertical Conveyor Reaper (VCR) is widely used for harvesting cereal crops.

The front-mounted VCR has a wider cutting width of 2100 mm, which demands more turning space at head-lands. Smaller rice field plots, traction, compaction problems and poor visibility from the operator's seat are the major disadvantages of such reapers (13).

Modern reapers now equipped with hydraulic systems, offering smoother and more efficient operations. To accommodate the diverse needs of farmers, some reapers are now designed to be compatible with mini tractors.

Sardar Reaper, Vasundra Krishi Yantra, Saeco Strips, Krishitech are some of the leading manufacturers of tractor operated reapers in the present era.

### Reaper binder

A reaper binder is a specialized harvesting machine that cuts and binds crops into small bundles for easy handling and transportation. Reaper binders are available in self-propelled, tractor-mounted and walk-behind models, making them suitable for small to medium-scale farming operations.

A tractor-operated reaper binder is equipped with cutting, gathering and knotting functions. The self-propelled unit provides improved manoeuvrability along with visibility and can be controlled by an operator (17). Self-propelled reaper binder cuts the crop and simultaneously bundles and discharges it between the drive wheels onto the ground. The cutting height varied from 50 to 70mm and manoeuvrability issues were also encountered. (18).

Recent models feature binding mechanisms, resulting in an increased number of bundles produced per minute. Some models offer adjustable binding settings to accommodate different crop sizes and field conditions. New materials like galvanized steel and polymer-coated parts have been reported extend the machine life. The quick-release mechanisms for cutter bars and binding units simplify maintenance and repairs, while sealed bearings and protective covers enhance performance under dusty conditions.

BCS, Sardar Reaper, Osaka International Inc., Aditya tractors, Ganga RK Industries are some of the current manufacturers of reaper binders.

### Thresher

Threshing is the process of detaching rice grains from the earhead through impact force (19). In developing countries, threshing is carried out by either human or animal power through methods such as foot treading, bundle beating, etc. (20). Other advanced power options include tractors, power tillers and electric powered motors. Portable threshers were also developed to reduce labour drudgery (21). Modern threshers significantly reduce grain damage and increase threshing efficiency. A thresher typically consists of a threshing cylinder, rasp bar (nylon or iron-based), a concave structure, a motor and a feeding inlet.

Threshers can be classified into different types based on its working that includes axial flow threshers and drummy threshers. Based on the power source, threshers can be categorized as Manual pedal operated, manual crank operated, animal operated and power operated. In the recent times, combine harvesting (discussed in following section) has become prevalent, wherein harvesting and threshing are carried out simultaneously using a single machine.

The important factors affecting the performance include concave clearance, peripheral speed, grain moisture content and feed rate (19). Additionally, the physico-mechanical properties of the crop (type of ear head, bond strength of the grain in the panicle, etc.,) determines a vital role in the selection of proper threshing mechanism to achieve maximum results (22).

### Combine harvesting

A combine harvester is a versatile machine commonly used to perform multiple harvesting operations, including cutting, threshing, separating and cleaning grains in a single pass.

Combine harvesters used for rice harvesting are classified based on their drive systems which includes self-propelled and tractor operated type, track type drive wheeled, track with a float operated (floating rice harvester) and pneumatic wheeled type. Meanwhile based on feed system, they are further categorized into head feed type, axial flow type and transverse type.

The combined harvester (Fig. 3) and self-propelled vertical conveyor reaper with thresher are more suitable for high and low farmland, respectively (23). The volume of current food production would be unthinkable without the application of combine harvesters (24). More than 75 % of the rice cropping is harvested using combines. Combine harvesting machines work best on well-drained relatively level farmlands, with a field layout that minimizes the number of turns in a field (25). In developed countries, most of the crops are harvested using combine harvesters (26), which performs multiple operations in a single pass, including cutting or stripping, gathering and uniform conveying (regulated by reel position and speed), threshing using a cylinder or rotor (with adjustable concave clearance and threshing speed), separation via rotor or straw walkers, aspiration of air (fan speed setting) to remove the chaff, mold spores and light particles and finally separation of threshed kernels by density and size of sieve openings and shaking mechanisms . In India, leading manufacturers of combine harvesters include CLAAS, Preet, Kartar, Sakthiman, Vishal, Swaraj and New Holland and imported manufacturers such as John Deere, Kubota and Yanmar machines. (27). A combine harvester typically consists of a header assembly, cutter bar, gathering and conveying system, threshing unit and a winnower.

A specific type of combine harvester, the head-feed combine (Fig. 4) only process the panicles (heads) of the crop while leaving most of the straw standing in the field. This is particularly useful in wetland rice harvesting, where excessive straw intake can cause clogging and inefficiency.

The harvesting machines and combine harvesters used for cereals are equipped with reciprocating cutting mechanism that utilizes standard-type knife edges with stroke length of 76.2 mm (24). For such standard-type knife edges, the velocity of knife section is expressed in Eqn 1.

.......(Eqn. 1)



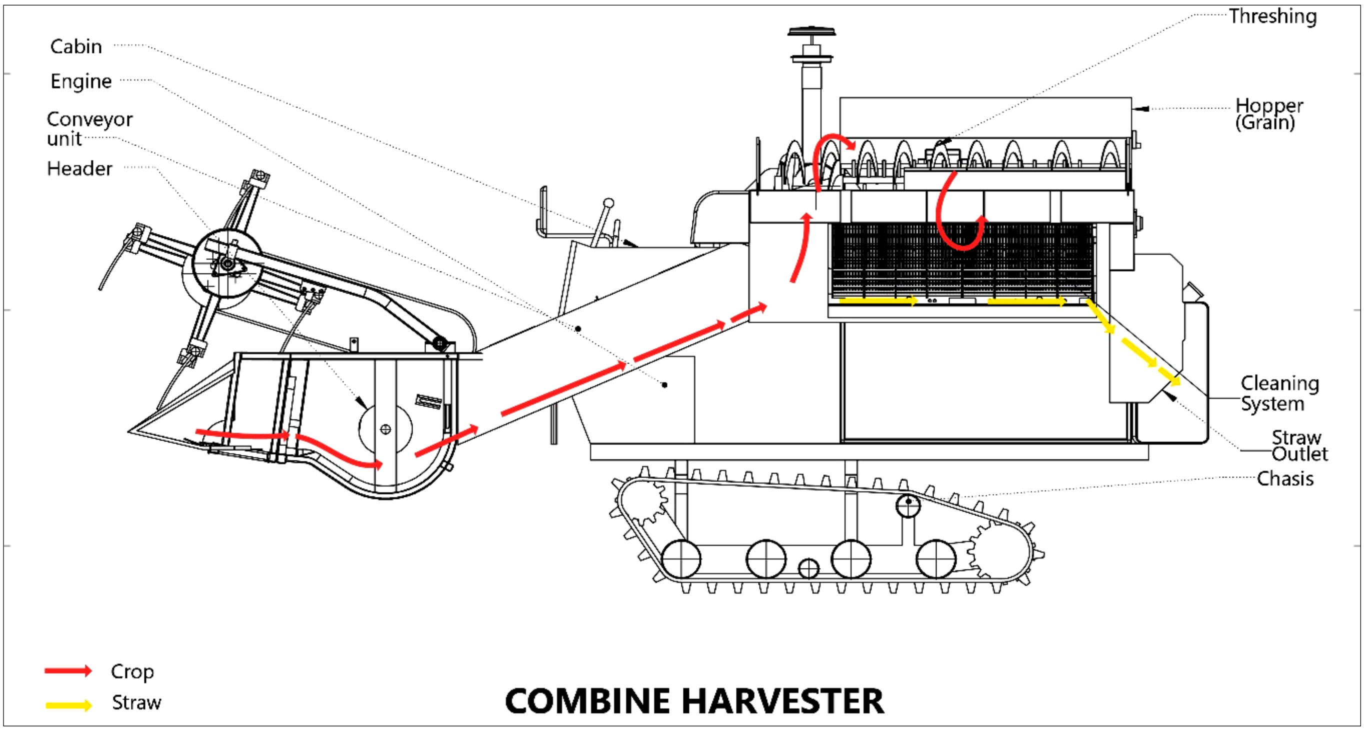



**Fig. 3.** Schematic of flow in a combined harvester (25).

**Fig. 4.** Head-feeding type combine harvester (77).

$$V_k = R \times V_m \qquad \text{(Eqn. 1)}$$

Where,

$V_k$ = Average knife velocity, m $s^{-1}$,

$V_m$ = For-ward speed of harvester, m $s^{-1}$

R = Cutting index.

The angle between the cutting edge and the axis of knife section (α) is 310 with a velocity of 1.5 m $s^{-1}$. The cutting index of available cutter knives typically ranges from 1.3 to 1.4 (28). The crank revolution count is calculated by the equation (29).

$$V_k = Sn_c/30 \qquad \text{(Eqn. 2)}$$

Where, $n_c$ = Number of crank revolutions

The reel index is defined as the ratio of reel's peripheral speed to the forward travel speed and it typically ranges from 1.25 to 1.5, depending on the crop conditions in the field (30).

$$\lambda\_i = u_t/v_m \qquad \text{(Eqn. 3)}$$

Where,

λ = Reel index,

$u_t$ = Tangential velocity of the tip of the bats, m $s^{-1}$

$v_m$ = Forward velocity, m $s^{-1}$

The absolute velocity of the reel should be greater than the forward speed of the harvester. The reel should touch the crop below the centre of gravity for optimal performance. Reel axis is typically placed 230 mm to 300 mm ahead of the cutter bar. The crop cutting height generally ranges between 150 mm to 250 mm whereas reel teeth clearance is maintained at 50 mm to 75 mm. A reel height of 87 cm was used for better results (31). During harvesting, the reel height is adjusted to ensure a uniform movement of crop into the cutter bar via a control panel (32).

A reel index of 1.7 was found to be ideal for combine harvesters operating on rice variety *Bg 94-1* in Srilanka, as it minimized header losses while maintaining both field capacity and field efficiency (33). At lower reel index values, the fingers failed to sweep the entire rice towards the header (34), whereas a higher reel index caused the fingers to strike the panicles aggressively resulting in increased losses. A reel index in the range of 1.25 to 1.5 is recommended to minimize head losses (35). However, the suitable value of the reel index may vary with the crop type and field conditions, but recommended reel index values should be lower than 1.5 (36). In non-lodging crops, the header losses were minimized when the reel index value was between 1.5 and 3.0 (37). It was observed that the reel index was increased with decreasing of reel velocity (33). Minimizing grain loss requires the manipulation of both magnitude and the direction of reel bar velocity (36).

The cutting efficiency and uniformity are affected by stroke length (38). Both blade and edge angle are two important factors that reduce shearing force and cutting energy thereby increasing the effective performance of cutter bars (39). A Turkish study analysed shearing force and shearing energy of rice stem as a function of blade angle, blade type and cutting speed. It was observed that a decrease in the blade edge angle from 90 to 50 °, led to increase in shearing force and energy values for rice stalk. At a blade edge angle of 90 °, the highest force and energy values were measured as 25.47 N and 5.8 N cm. The effect of loading speed on the cutting parameters such as cutting forces, cutting energy, cutting strength and specific cutting energy was found to be significant. The highest values of shearing force and energy were found at 2 m $s^{-1}$ loading speed and the lowest values occurred at a cutting speed of 6 mm $s^{-1}$ (40).

To collect and bruise the rice straw and stubble left in the field after combine harvesting, a locally developed machine (tractor operated) commonly known as 'straw combine' or 'straw reaper' is used. The components of the straw reaper comprise of stubble cutting and feeding units, straw bruising and blowing units and a straw collection unit equipped with a wire mesh enclosed trailer (41). Balers and rakes have limited application, due to the minimal use of rice straw (42). In North India, about 85 to 90 % of this rice straw is burnt in the fields followed by wheat sowing as the conventional method. Although mechanization for rice harvesting exist, there is only limited published research with evaluation performance data for rice residue management before sowing. Hence efficient mechanization with straw management is the need of the hour.

The operator must maintain a ground speed low enough to provide ample time for uniform threshing and good separation (43). The performance of combine harvesters in rice harvesting is influenced by both machine adjustments and the ability of the operator (44-50). The design of a robust automatic guidance system for a combine harvester (51) further assists in its efficient operation. The automatic steering system controls the harvester based on the measured position of the swath on the field.

Minimal turning radius, losses, operation time, increased ground clearance, power tiller operated combine harvester are some of the recent trends in combine harvesting. Intelligent Harvesting System provides real-time data on harvested areas, live location tracking, distance travelled and fuel consumption.

Combine harvesters are larger in size that the tractor, have more blind spots, making them more prone to accidents. Hence a system like 360 ° camera, proximity sensors, AI based warning systems etc can assist the operator to avoid such accidents. As of now, fully electric combine harvesters are not commercially available on a large scale. The primary challenges hindering their development include the substantial energy requirements for harvesting operations and the limitations of associated battery technology.

## Evaluation of harvesting machine

The evaluation of various harvesting machines has been carried out by several researchers and is discussed as follows. Research has shown that a combine harvester equipped with a head stripper of 3 m width, had a field capacity and field efficiency of 0.66 $hah^{-1}$ and 74 % for standing crop and 0.3 ha $h^{-1}$ and 72 % for lodged crop, respectively (53). Another research observed that field performance of a portable reaper exhibited a field capacity of 0.15 ha $h^{-1}$ (54). The average cutting efficiency of 98 % and an actual field capacity of 0.24 ha $h^{-1}$ was observed in a separate study on power reaper (16). The field capacity of a tractor-operated combine harvester varies from 2.88 to 3.60 ha $h^{-1}$ (55). The tractor-mounted straw reaper field capacity was measured as 0.20 $hah^{-1}$ (56). Additionally, it was observed that if the travel speed of rice combine harvester is increased from 0.8 to 2.9 $kmh^{-1}$, the field efficiency of the combine declines (46).

Another study (57) identified 9 attributes that consumers consider essential in the design of a rice harvesting machine: portable, maximum speed, multifunctional, lightweight, easy to disassemble, cheap, ergonomic, easy to maintain and spare parts easily available. Using the quality function deployment technique, several technical requirements were identified to meet consumer needs, including blade design, material type, motor drive, wheel, unloading slot and long handle knife. Rice harvester designs with such requirements can be used in undulated lands in Indonesia and can be used to increase rice harvesting capacity. The requirements of water-logged rice harvesting machine were also discussed (58). Additionally, several designs and developments were made using floating barge-assisted harvesting machinery (59, 60).

## Advanced technologies

Autonomous machinery for harvesting rice is a much-appreciated aspect of smart agriculture. Development of turn algorithms (61), navigation technology (62) and path planning (63) represents key advancements.

Yield monitoring systems assess rice yield (64) for spatial land variations. The major components of a yield monitoring system include GPS, grain flow sensor, grain moisture sensor, cutting width sensor, vehicle speed sensor, header position sensor, monitoring system display, etc. Variable rate technology is an emerging innovation in rice production (65). Variable rate technology utilizes the data acquired from yield monitoring system to assess the nutrition deficit levels in the field, thereby optimizing the fertilizer input and better yield. Additionally, sensing technologies have been employed to analyse the rice grain loss awhile harvesting (66).

Furthermore, the enhancement of mechanization with the advent of 5G network supports connectivity features of rice harvesting machines and their associated technologies (67). Additionally, an emergence of 6G and 7G networks are expected.

Electric machinery for paddy harvesting is beginning to gain momentum. Educating farmers about the benefits and operation of such machinery is vital for successful implementation. However, electric and hybrid machines often involve high upfront costs. For Indian farmers, particularly for small-scale operators, these costs can be prohibitive without adequate subsidies or financial support.

Solar energy is also revolutionizing the agricultural sector through it's various applications such as irrigation pumps, sprayers, weeders, etc. Rice harvesting machine powered by solar energy was investigated by several researchers for their feasibility (68, 69).

Such technologies are expected to occupy a significant share of paddy machinery market.

### Achievements of Mechanization

The average cost, time and grain loss that achieved by utilizing combine harvester over manual harvesting methods are 35 %, 97.50 % and 2.75 %, respectively (70). In Indonesia, application of technology in the rice harvest, increased farmers' income by 44 % (71). A comparative study between a rice reaper and a labour reported that, a reaper is 14 times more efficient than a daily labourer in cutting and placing cereals in the field (72). Furthermore, the rice seed harvested and threshed by both manual method and combine harvesting method with minimum mechanical damage will not affect the germination and seedling vigour irrespective of the rice varieties (73). Moreover, labour requirements for reaper and manual harvesting was observed to be 4 and 28 man-$hha^{-1}$ respectively with a cost saving of 67 % when compared to manual harvesting (16).

Operators must be adequately trained to understand each of the unit processes of the combine. Additionally, a study from Indonesia, indicates that larger farm size, trainings provided by government agricultural extension officers and long-term farming experience promotes the adoption of mechanized rice harvester including combine harvesters (74). A low cost combine harvester was developed and tested for rice and wheat cultivation in India, demonstrating its suitability for small- scale farmers (75). However, negative effects of rice harvest mechanization have been observed on the employment and income of the harvesting labourers (76).

### Handling losses

Shattering loss is defined as the amount of the grains and ear heads that fall on the ground due to the shattering action. On the other hand, collection loss is defined as the amount of grain and ear heads lost during windrowing, collection and bundling of the crop. As discussed earlier, the stage of harvesting has a significant impact on the harvesting losses Therefore, it's necessary to follow harvesting at the right stage by utilizing suitable machine parameters to avoid losses. The operator must adjust the machine systems according to the crop and field conditions.

While reaping and threshing are performed individually, the harvested crop mass is subjected to environmental factors resulting in significant changes in moisture content and associated losses. Comparing to indirect methods (Reaping and threshing), direct method (Combined harvesting) had low harvest lost, particularly while employing head feed type combine harvester (78). In combine harvesters, the primary source of loss is observed at two main parts, such as cutting and threshing units. Incorporating suitable conveying mechanism helps to stop clogging and reduces cutting- related losses.

Fast driving is one of the most common causes of higher combine losses (43). According to American Society of Agricultural and Biological Engineers (ASABE), a typical forward speed of combine harvesters is5 $kmh^{-1}$. Studies indicate that, increasing the travel speed of self-propelled rice combine harvesters from 0.8 to 2.9 $kmh^{-1}$, significantly increases grain loss (46). Additionally, harvesting opera-tion exhibited increased fuel consumption as the total working time increased (77). However, fuel consumption can be lowered when a combine-harvester equipped with single a threshing-separation rotor is stopped at idle periods (79). Notably, harvesting losses are not directly dependent on combine age, rather, it is affected by factors such as combine adjustment and maintenance, operator skill, product yield and field conditions (80).

grain losses during harvesting using area per binder were less than 1 %, while manual harvesting resulted in approximately 4 % loss (18). A vacuum inhalation mechanism was developed to collect the rice grains that fall on to the ground.

### Cost economics

The need for large numbers of seasonal labourers diminishes with mechanization. This in turn reduces the cost of paddy harvesting, particularly in the regions where high labour wage prevails.

Harvesting accounts fora significant variable cost of 17.17 % in a study (81). While manual and reaper harvesting techniques may incur similar expenses, combine harvesting has shown significant reduction in expense. According to studies, the use of combine harvesters has led to cost reductions ranging from 14 % (82) to 57 % (83) compared to the manual harvesting methods.

## Conclusion

In India, harvesting of cereal crops is one of the major attentive operations in agriculture, which demands a significant number of labours. The review concludes that extensive research is being carried out towards the mechanization of rice all over the world. Additionally, the researchers have highlighted the limitations relating to harvesting time, mechanism and operational parameters along with their optimum range for higher yield or efficiency. These optimum range may vary slightly based on the crop variety, field conditions and machine parameters which should be adjusted accordingly Further focus is recommended on integrating advanced technologies such as Artificial Intelligence, Geographical Indication System and spatial mapping for harvest data collection. The adoption of autonomous harvesting machines capable of self-navigation for efficient operation, autonomous adjustments such as cutting heights and speeds could significantly enhance performance as has been demonstrated in other agricultural operations.

## Authors' contributions

All authors have contributed equally to the conception, design and drafting of this review article.

## Compliance with ethical standards

**Conflict of interest:** The authors declare that there is no conflict of interest regarding the publication of this paper.

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