Review of precision rice hill-drop drilling technology and machine for paddy

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Abstract: Mechanized rice direct seeding is a cost-effective and efficient approach for rice cultivation. Recently, the use of rice direct seeding has been increasing rapidly owing to rural labour shortages and continuous increases in agricultural production costs. This article reviews the research and application progress of mechanized rice direct seeding including direct seeding technologies, precision rice seeding, precision rice seed-metering devices, key supporting agronomy technologies for mechanized rice direct seeding. South China Agricultural University developed precision rice hill-drop drilling (PRHDD) with synchronous furrowing and ridging technology and series machines for paddy that affords remarkable advantages in terms of saving time and labour, higher yield, and higher efficiency. In this approach, pre-germinated seeds are uniformly hill-dropped in the expected positions in puddled soil. It significantly improved the crop growth population and effectively solved the problems of high frequency of disease and pests caused by the irregular distribution of rice seeds with manual broadcasting, and generally reduces seed usage and increases the yield. Therefore, this technology has broad application prospects and great potential for promoting the development of mechanized rice direct seeding in China.
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1 Introduction

Rice is an important staple food crop in the world. Its cultivated area worldwide is 160 million hm^2, and this accounts for 22.3% of the total crop planting area. The gross product of rice is 741 million t, and this accounts for up to 26.0% of global grain output[1] (FAO, 2017). Rice clearly plays an indispensable role in global food security. At present, global grain and food security are being greatly affected by many factors such as population, arable land, climate, and resources. Therefore, it is important to achieve good quality, high yield, improved efficiency, and sustainability of rice production and to accelerate rice industrialization to ensure long-term food security.

Mechanization is crucial for improving rice production. Among all steps in rice production, planting is the most complex, labour-intensive, and difficult to mechanize, and it greatly influences the production quality and final output of rice. At present, rice planting mechanization remains underdeveloped in China with an average level of only 44.45%; this is lower than that of other food crops and even that of rice ploughing and harvesting itself.

Owing to rural labour transfer to cities[2,3], changing land transfer policies, and high costs, the growth rate of mechanical transplanting is decreasing. Rice direct seeding has been a less labour-intensive, high-efficiency, and simple method to cultivate rice. There are three main rice direct seeding methods[3,4]: rice dry direct seeding (RDDS), in which dry seeds are sown in dry soil to depths of 1-3 cm before irrigation[5-7]; rice water direct seeding in which seeds are sown into standing water on ploughed dry land[8-10]; and rice wet direct seeding (RWDS), in which pre-germinated seeds are sown in wet puddled-precipitated-drained soils[11-13].

Comparing with transplanting, rice direct seeding saves water[14-19] and reduces greenhouse gas (GHG) emissions[20-23]. Therefore, rice direct seeding mechanization is one of the most simple, effective, and sustainable ways to cope with labour shortages and high production costs[24-32].

South China Agricultural University developed a precision rice hill-drop drilling (PRHDD) technology with synchronous furrowing and ridging for wet paddy. In this approach, pre-germinated seeds are uniformly hill-dropped in the expected positions in puddled soil. It significantly improves the crop growth population and effectively solves the problems of high frequency of disease and pests caused by the irregular distribution

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of rice seeds with manual broadcasting, and generally reduces seed usage and increases yield[33,34]. Therefore, PRHDD has become an important development direction for mechanized rice direct seeding in China.

This study aims to analyse the research progress and application status of PRHDD technology and machinery with synchronous furrowing and ridging as well as key related agronomic techniques to provide references for the promotion and application of PRHDD technology.

2 Status of mechanized rice direct seeding

2.1 Worldwide status of mechanized rice direct seeding

USA has the largest rice planting area among Euro-American countries with 1253 thousand hm^2 and the yield of 8 t/hm^2 in 2016. The main rice planting areas are in the Mississippi River, Arkansas, and California, with Arkansas alone accounting for around half of the total planting area in USA[35]. The two main rice planting methods used in USA are aerial seed planting (20%) and mechanical drilling (80%).

Italy has the largest rice planting area in Europe with 234 thousand hm^2 and the yield of 6.7 t/hm^2[1]. The main rice planting areas are Pavia, Vercelli, and Novara in northern Italy[36,37]. The rice planting area in Italy is one-third of the total rice planting area in Europe (665 thousand hm^2). Vercelli produces 33% of Italy's rice yield, and it uses the most advanced rice production technologies in Italy[38]. Since the 1960s, Italy has shifted from transplanting to mechanized RDDS[39].

In Australia the rice planting area has decreased significantly from 113 thousand hm^2 in 2013 to only 27 thousand hm^2 in 2016[1]. However, Australia has the world's highest mean rice yield at 10 t/hm^2. Australia mainly uses mechanized rice planting methods such as RWDS and RDDS[36].

In Japan, rice is the main food crop, and its planting area accounts for more than 80% of the total food crop planting area[1]. During the 1960s and 1970s, many studies focused on rice direct seeding technology, and the direct seeding area reached 55 thousand hm^2. Mechanical transplanting is used for planting 99% of rice[40], with the growing maturity of the technology of rice transplanter. By the end of the 20th century, with increasing labour shortages and production costs, the direct seeding area increased from 8.9 thousand hm^2 in 2000 to 27 thousand hm^2 in 2014[41]. The mechanized direct seeding technologies used include RDDS, water direct seeding, and RWDS[42-45].

In Korea, rice is the most important food crop too. Since 2012, the rice planting area has been decreasing, reaching 779 thousand hm^2 in 2016, although the total grain yield has remained stable at 5.6 million t[1]. In the 1970s, South Korea introduced mechanical transplanting technology from Japan and rapidly increased rice planting. With rapid urbanization, rural labour has largely transferred, and therefore, the direct seeding area has been increasing. In the 1990s, researchers began studying mechanized direct seeding technique[46]. Thus far, Korea has mainly used RWDS, followed by RDDS and water direct seeding (aerial seed planting)[47].

In India, the rice planting area was 43 million hm^2 in 2016, being around 1.3 times as much as that in China and the highest in the world. However, its total grain yield was 160 million t, being around three-fourths of that of China.

The reason why these developed Euro-American countries can produce high yield of rice, is not only relating to rice varieties and soil climatic conditions, but also high precision direct seeding technology. The mechanization of rice production level of most Asian countries is far behind the developed countries. Meanwhile, they produce less rice. Obviously, rice yield is positively correlated with mechanization level. Therefore, it is urgent to improve the mechanization level of rice production.

2.2 Mechanized rice direct seeding in China

China is one of the major rice-producing countries with the largest total rice yield (27%) in the world. In 2014, 2015, and 2016, its rice yields were 207, 208, and 210 million t, accounting for 37.0%, 36.4%, and 36.0% of China's total grain crop yield and 27.8%, 28.1%, and 28.2% of the world's total rice yield, respectively[1]. China's rice planting mechanization level currently exceeds 40%. China's "Thirteenth Five-Year Plan" has proposed to increase rice-planting mechanization level to 60%.

Historical records shows that China has a long history of using rice direct seeding, with technology for the same being developed during the Han Dynasty. The Chinese government has introduced rice seedling mechanized transplanting methods over the years owing to their relatively stable total rice yield. However, high cost and labor intensity were also attached. Declining rural labour forces and increasing labour costs have increased the growth of mechanical direct seeding in suitable areas rapidly. Therefore, mechanical direct seeding shows high potential for achieving 20% growth of rice planting mechanization level in five years[48].

China has a large rice planting area (20°N–50°N, 75°E–150°E), and the climate and soil vary greatly. Therefore, there are regional distribution differences between RDDS and RWDS. During the rice seeding season, RDDS is suitable in northern China (Xinjiang, Ningxia, etc.) where there is less rainwater. By contrast, RWDS is suitable in southern China where there are many spring rains owing to the monsoon climate[6]. Rice water direct seeding is not used commonly in Asia[49,50]. The pulp method is generally used in paddy fields[51], where the flow of the water and mud layers is not conducive to rice rooting and seedling. Meanwhile, water direct seeding requires a large number of seeds to reduce the effect of uneven density produced by seed drift and therefore ensure adequate planting density[5]. Intensive agriculture and precision planting modes can increase the utilization and output of agricultural resources[52-55]. Therefore, the Euro-American aerial seed planting mode with water is not applicable from the perspective of China's basic national conditions with fewer resources per capita.

The research team of South China Agricultural University invented PRHDD technology with synchronous furrowing and ridging to meet the agronomy requirements of different regions, rice cycles, and varieties to address the problems faced with manual broadcasting, field growth disorder, low group quality, and poor resistance.

PRHDD with synchronous furrowing and ridging opens water furrows and seed furrows in the field synchronously. Then, rice seeds are sowed into the seed furrow by hill-drop drilling to achieve hill-in-row growth and ridge planting (Figure 1). The soil on the seeding furrow wall will be backfilled to cover the seeds and increase the rice root penetration depth with the scouring of rainwater. This increases the soil redox potential, which is favourable for root growth and root structure improvement owing to less ridge flooding. The results showed that PRHDD reduced yellow roots by 20% and black roots by 13% and increased white roots by 33% compared to manual broadcasting. The water furrow between ridges provided water for rice growth without entire surface irrigation, thus reducing the irrigation water needed by more than 30%. Rice is a group crop, and hill-drop drilling provides balanced space for its growth. Multigrain polygamy in the hills is conducive to top soil emergence, competition with each other, and high-yield group establishment.

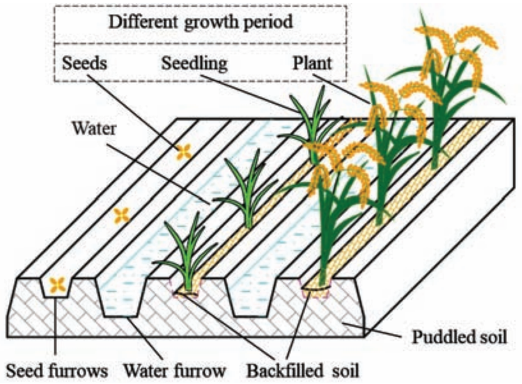


Figure 1 The principle of synchronous furrowing and ridging hill-drop drilling for wet paddy

3 Review of precision rice metering devices

The seed metering device is a key part of a direct seeding machine. Rice direct seeding machines have two main types of metering devices: mechanical and vacuum. Mechanical drillers equipped with grooved roller-type metering devices are widely used in developed countries such as USA, Australia, and European countries. This metering device is simple and cheap, and it is easy to adjust the sowing rate and adapt to high working speeds[56]. A spiral grooved metering device can improve the seed distribution uniformity in the sowed row[57,58]. Amasone designed control seed wheels (Figure 2) with sowing rate adjustable from 1.5 to 400 kg/hm^2 and high precision[59].

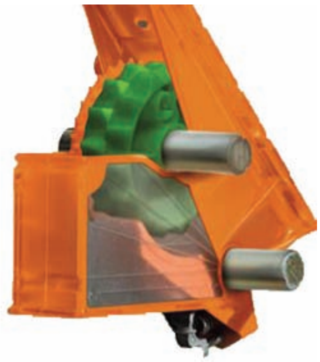


Figure 2 Schematic view of control seed wheels

A pneumatic metering system includes a large grooved roller, a fan, a pipeline, and one (or more) seed equator (s). Seeds dropped from a large grooved metering roll are mixed with the air flow generated by a fan, and the seeds are blown to the seed equator through the pipeline. Then, the seeds are sown in the opened seed furrow[60]. A multi-in-one (multiple sowing pipes mounted on one seed equator) pneumatic metering system simplifies this mechanism, and it is mainly used in large wide seeders.

In Japan and Korea, grooved roller-type metering devices are most popularly used for direct seeding. Currently, direct seeding metering devices used for both row drilling and hill-drop drilling machines have been improved based on a roller-type metering device (Figure 4) designed by Ryu[56] and Yoo et al.[61]. The sowing rate can be adjusted by adjusting the opening gap of the grooves on the roll surface. Togashi[62] and Tasaka et al.[63] studied a shooting gun metering device (Figure 5) in which a saw-tooth disc rotates at a certain speed and hits seeds dropped continuously from a pipe to accelerate them. The seeds are hill-dropped into the soil based on the time intervals at which adjacent saw-teeth hit the seeds. Experimental results showed that the hill-drop effect was the best when the saw-tooth disc diameter was 190 mm, thickness was 20 mm, number of teeth was 32, and material was elastic; gap regulation of saw-tooth disc and tube was 1-3 mm; seed tube length was 190 mm, diameter of long and short sides was 28-30 mm and 23-25 mm, respectively; and angle θ was 10°-15°.

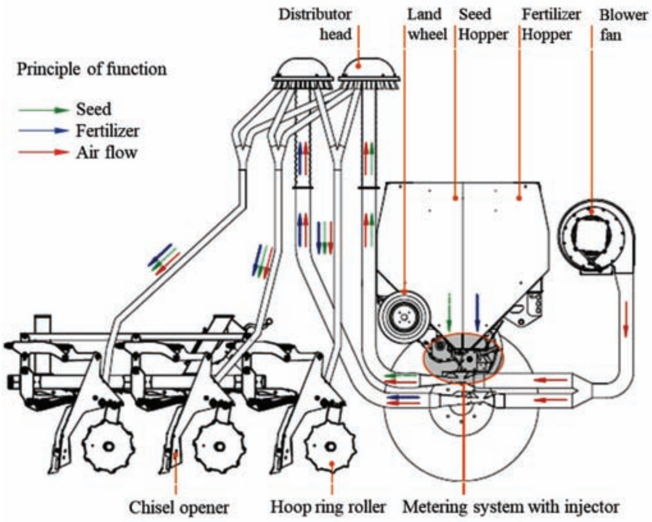


Figure 3 Schematic view of pneumatic metering system

Figure 4 Schematic view of roller-type metering device

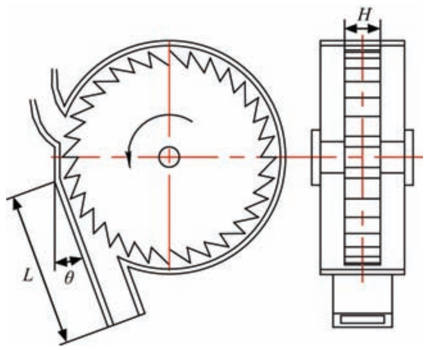


Figure 5 Schematic view of shooting gun metering device

In China, various seed metering devices have been developed to achieve precision rice direct seeding for different rice varieties. RDDS requires a higher sowing rate and working speed, as well as soil with low water content. Therefore, seeds bounce when they are dropped on the soil, making it very difficult to achieve hill-drop drilling without using any special devices. As a result, few existing metering devices are suitable for precision rice hill-drop drilling for dry land.

Zhang et al.[64] from Huazhong Agricultural University designed a pneumatic cylinder-type precision direct seed-metering device, shown in Figure 6. This device features a conical-shaped hole, multi-suction hole filling, flexible cord for gas-blowing of seeds, flexible guard seed banding, and gas blow prevention. CFD software was used to simulate the airflow field in different holes and experiments were conducted to determine the optimal parameters of the seed metering device. Bench test and field experiment results showed that the pneumatic cylinder-type precision direct seed-metering device can meet the fine sowing requirement of hybrid rice. Huazhong Agricultural University designed a double-chamber side-filling-type metering device with a curved brush seed protection apparatus[65]. They used single-chamber sowing for hybrid rice and double-chamber sowing for conventional rice. The structure of the seed disk diameter, number of holes, hole diameter, hole depth, hole position, seed brush, and anti-blocking device were determined through theoretical calculations and experiments.

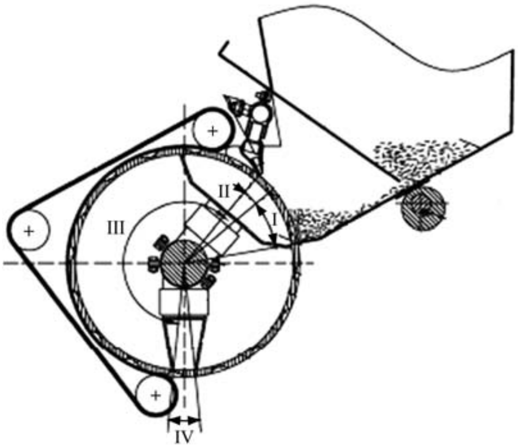
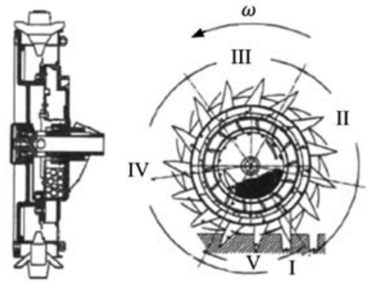


Figure 6 Structure diagram of pneumatic cylinder-type precision direct seed-metering device

The Xinjiang Production and Construction Corps (China) modified a duckbill membrane perforated cotton seed metering device, as shown in Figure 7[66]. The modified device filled seeds after it reached the planting zone, and the duckbill tapped into the soil. Then, the duckbill opened to release seeds. As the duckbill reaches a certain depth into the soil, seeds do not bounce, resulting in better seeding. However, the sowing rate and hill distance adjustment in this device were not convenient. Chen et al.[67] developed a gas-suction seed metering device with a tape guide. This device synchronized the seeds and the seeder and enveloped seeds in the guide belt and guard plate formed in the cavity while the top of metering device transported seeds. Seeds fall freely when close to sowing location to complete seeding. Because the seed furrow is close to the seeding point, it can solve the problem of seed bouncing.

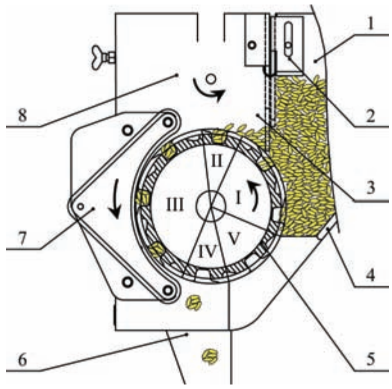
South China Agricultural University studied the interaction mechanism between the rice seed and the metering device from the viewpoint of wide planting area, large variety, and fine sowing requirement of rice. They determined the flow characteristics of different rice varieties as well as their corresponding filling mechanisms and seeding laws. They developed three types of PRHDD seeding devices for different regions, different varieties, and different sowing approaches of rice.

For sowing rate requirements of 30-75 kg/hm^2 of conventional and hybrid rice varieties, a combined hole-type metering device with adjustable sowing rate[68] was developed, as shown in Figure 8. This device used combination type-holes and a double-chamber filling mode with elastic follow-up protecting method. This improved the uniformity of rice seeding, reduced the rice damage rate to 0.2%, and achieved sowing rate adjustment of 3-20 seeds per hill.



Note: I. Suction area; II. Cleaning area; III. Transport area; IV. Dropping area, V. Hill-drop area.

Figure 7 Schematic diagram of duckbill metering device configuration



1. First filling place 2. Seeds flow adjusting device 3. Second filling place 4. Unload plate 5. Combined hole-type roll 6. Tube 7. Protecting device 8. Cleaning device.
I. Filling area II. Cleaning area III. Protecting area IV. Dropping area V. Transition area.

Figure 8 Structure diagram of combined hole-type metering device

For the sowing requirement of 15-30 kg/hm^2 for some hybrid and super-rice varieties, a vacuum vertical disc metering device was developed[69-71], as shown in Figure 9. This device applied negative pressure sucking, seed introduction through guide teeth, and a stratified diversion mode. Airflow characteristics were used to carry and transport seeds and thus improve the adaptability of seeds, reduce the seed damage rate, and improve the sowing accuracy. Production test results showed that the vacuum disc metering device can adapt to various super hybrid rice varieties with 95% of 1-3 seeds per hill and less than 2% missing rate.

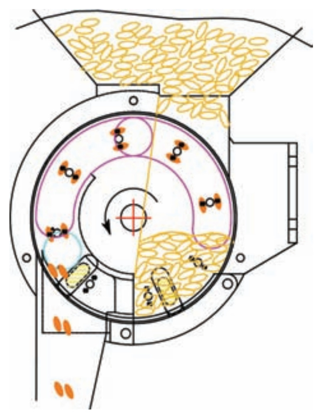


Figure 9 Configuration of vacuum vertical disc metering device

Another vacuum drum metering device (Figure 10) was developed for direct seeding of 15-30 kg/hm^2. This device comprised inner and outer cylinders, a lateral sucking mechanism, and a guide tube. Different sowing rates were achieved through the control of the outer hole and the suction and discharge air pressure. The air flow and guide tube were adjustable so as to achieve 91.6% probability of placing (2±1) seeds in each hole and only 2.7% probability of a hole being left empty.

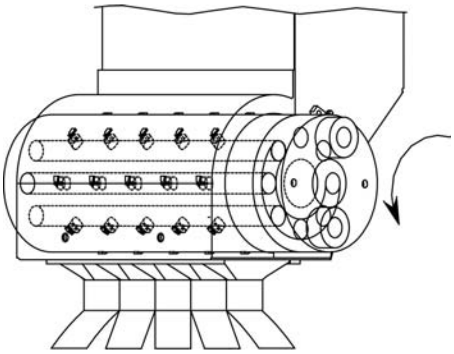


Figure 10 Configuration of vacuum drum metering device

4 Application status of precision direct seeding machine

4.1 Worldwide application of precision direct seeding machine

In Euro-American countries, mechanical (Figure 11a) and pneumatic (Figure 11b) direct seeding machine s are used for both rice and wheat drill seeding. Pneumatic direct seeding machine were used in air-drilling seeding. Mechanical direct seeding machine s show higher accuracy than Pneumatic direct seeding machine s because they use a grooved roll or independent double-row gear metering device. The most well-known direct seeding machine manufacturers worldwide are Amasone in Germany, MaterMacc and Maschio Gaspardo in Italy, and John Deere in America. These manufactures have developed some mechanical and pneumatic seed drills with different structures and configurations for different applications.

a. Mechanical seed drills b. Pneumatic seed drills

Figure 11 Large area seed drills used in developed countries

Kajitani[72] from Japan has developed a no-tillage and RDDS with the working principle similar to that of a duckbill cotton seed metering device. It uses a puncher mounted on the periphery of a rotating disk to drill the seeds into the soil, and the seeding door is synchronously opened by the force from contact with the ground. Hill-drop drilling could be realized by releasing seeds and fertilizer into soil and covering the soil. Yashiro[73] developed an RDDS with rotary tillage. After rotary tillage and crumbling of the soil, the furrower rotates automatically and creates a seed furrow. The seed-metering device sows seeds into the bottom of the furrow, then the furrows will be covered with soil when water floods.

Iseki and Yanmar have jointly developed an rice direct seeding machine with the chassis of a transplanter. This device could profile and open seed furrows synchronously and use a roller-type metering device to sow seeds on the paddy surface[74-77]. Chosa[78] and Furuhata[79] developed an air-assisted strip seeder. This seed-metering device has two rows of pipe. The device sends seeds into a tube, and the airflow generated by the rear fan is sent into different seeding tubes through the distributor to blow seeds through the injection port. As the metering nozzle is narrowed, the flow speed increases, and seeds are injected into the soil faster.

Kubota, Iseki, and Yanmar are the three largest Japanese agricultural machinery companies, and manufacture good-quality paddy field machines. Their rice transplanters are dominant in the Asian market. These companies develop rice direct seeding machines powered by a high-speed rice transplanter chassis (Figure 12). Furrowers are mounted at the bottom of the pontoons. The middle pontoon is used to sense the ground surface for profiling and to sow seeds into seed furrows. However, this type of seeder is only used in Japan currently.

Figure 12 Precision direct seeding machine (Kubota)

Most of the rice planting machines and technology used in Korea are introduced from Japan. In response to the demands of direct seeding in both paddy fields and dryland, a new type of multifunctional rice direct seeding machine (Figure 13) was developed in Korea. This machine was powered by tractor. It used a spiral filling device to level the land and to eliminate wheel tracks. Rice seeds and fertilizers were sown into the seed furrows and fertilization furrows, respectively, and covered with soil. This seeder can be used in both wet puddled fields and dryland[80].

Figure 13 Multifunctional rice hill-drop drilling machine

4.2 Application status of precision rice direct seeding machine in China

Owing to rural labour shortages in China, the advantages of time-saving, labour-saving, and low labour intensity of rice direct seeding technologies are considered promising. Therefore, many studies have been investigating PRHDD in recent years. Various types of rice s have been developed and popularized.

Initial rice s included simple rice drillers such as the Shanghai

Hujia 2BD series rice. It did not open the seed furrow, and seeds were directly sown onto the muddy surface with an outer sheave seeding device. In 2011, Nanjing Agricultural University developed a precision RPDDH machine[81] with an intermittent-drive seeding mechanism to drive the horizontal disc-type seeding device. However, the seed number of each hill cannot be adjusted, and the sowing rate could only be adjusted by adjusting the hill spacing. Nanjing Institute of Agricultural Mechanization developed a 33-row pneumatic row-type rice with a folding frame with a working width of 8 m and working speed of 10 km/h to meet the planting requirements of farms of various scales. Jiangsu Agricultural Machinery Extension Station developed a belt-type rice direct seeding with a furrower under the plastic baseplate. This device could only open a very shallow seed furrow, and therefore, it was not very useful for sowing. Anhui Agricultural University[82] developed an rice direct seeding machine with an eight-way circular groove push and spoon wheel-type seed-metering device that was powered by a paddy rice transplanter. This machine could achieve ditching furrow and precise direct seeding synchronously, with 8 seeding rows, 250 mm row space, and hill spacing range of 100-240 mm. However, this machine had no profiling mechanism, and it required flat and compact soil before seeding.

At present, the most popular PRHDD machine in China is a synchronous furrowing and ridging PRHDD machine (Figure 14) developed by South China Agricultural University[83-85]. This machine can perform synchronized furrowing, ridging, and precise hill-drop drilling, and it has adjustable hill spacing, optional row spacing, and profiling operations.

Figure 14 Structure diagram of precision rice hill-drop drilling machine

The PRHDD machine uses a transplanter chassis to provide power for moving and seeding. The hydraulic cylinder and lifting frame are installed on the back of the transplanter chassis. The slide board always clings to the mud surface owing to the effect of the altimetric and horizontal profiles. The seed and water furrows are formed as the machine moves forward. The seed-metering device is driven by a power transmission system, and it sows seeds into the seed furrows. The fenders on both sides prevent the influx of water and mud into the seeding area[86].

Using PRHDD with synchronous furrowing and ridging technology, the rice can grow well in a well-formed orderly manner with good ventilation and light to improve the emergence rate of rice, lodging resistance ability of direct seeding rice, and yield and quality of rice[87].

To meet the demands of different regions, South China Agricultural University developed a series of RWDS machines (Figure15).

1) The simplified PRHDD machine (Figure15a) is powered by a diesel engine, and it uses a hole-type seed-metering device to sow seeds into a seed furrow. However, owing to its low operating efficiency, this machine is mainly used only in small fields in hilly areas.

2) The PRHDD machine with synchronous side deep fertilizing (Figure 15b) opens fertilizer furrows in the middle of two seed furrows[88]. This fertilizer is applied to rice in two seed furrows, thus reducing the fertilizer cost and increasing the total yield of rice.

3) The PRHDD machine with synchronous spraying (Figure 15c) can spray herbicide or a liquid film synchronously with hill-drop drilling. The herbicide controls weeds in the early growth stage of rice, and the liquid film can reduce the influence of low temperature on seedling emergence.

4) The PRHDD machine with a vacuum vertical disc (Figure 15d) and drum (Figure 15e) can be applied to hybrid rice, especially super hybrid rice, with seeding rate of 1-3 seeds per hill[89].

5) The wide PRHDD machine powered by a wheeled tractor (Figure 15f) uses the hydraulic folding method to facilitate transferring on the road, and it uses a spiral mechanism to eliminate wheel tracks[90]. It can synchronously perform profiling, furrowing, and ridging. It has 21 seeding rows with working width of 4.5 m; this significantly increases its working efficiency and enables application to large-scale farms.

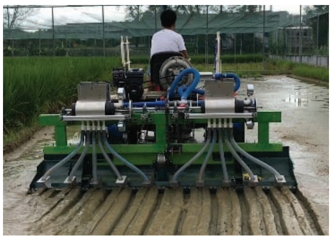
Table 1 shows the main specifications of different types of PRHDD machines currently used in China.

a. Simplified PRHDD machine

b. PRHDD machine with synchronous side deep fertilizing

c. PRHDD machine with synchronous spraying

d. PRHDD machine with a vacuum vertical disc



e. PRHDD machine with a vacuum vertical drum

f. Wide PRHDD machine

Figure 15 Different series of hill-drop drilling machine for rice for wet paddy

Table 1 Main operating parameters of different hill-drop drilling machines for wet paddy

No.	Varieties of seeder	Varieties of metering device	Varieties of rice	Efficiency ha/h (Speed m/s)	Seeding bed	Seeds per hill (Sowing rate /kg/ha)
1	Precision direct seeding machine (Kubota)	Roller-type	Conventional rice Hybrid rice	1.5	Surface	3–15 (30–75/ 75–225)
2	Precision rice hill-drop drilling machine	Combined hole-type	Conventional rice Hybrid rice	1.5	Seed furrow	3–10/ 10–15 (30–75/ 75–225)
3	Simple type rice direct-seeder	Combined hole-type	Conventional rice Hybrid rice	0.5	Seed furrow	3–10 (30–100)
4	Vacuum disc rice direct-seeder	Vacuum disc	Hybrid rice	1	Seed furrow	1–3 (15-30)
5	Vacuum drum rice direct-seeder	Vacuum drum	Hybrid rice	1	Seed furrow	1–3 (15-30)
6	Synchronous side deep fertilizing with rice hill-drop drilling machine	Combined hole-type	Conventional rice Hybrid rice	1.5	Seed furrow	3–10/ 10–15 (30–75/ 75–225)
7	Wide precision rice hill-drop drilling machine	Combined hole-type	Conventional rice Hybrid rice	1	Seed furrow	3–10/ 10–15 (30–75/ 75–225)

5 Agronomic technical issues in mechanized rice direct seeding

5.1 Rice varieties

Rice varieties used for direct seeding should have the following characteristics. (1) A strong ability to break through the soil for the emergence of seedlings. (2) A strong ability to resist lodging. Crop lodging affects the rice yield and quality, and it is not easy with mechanical harvesting. Studies show that the varieties which plants are shorter, stems are sturdier, and root systems proliferate sufficiently, will have strong lodging resistance[91-93]. Most Chinese varieties currently adapt to transplant, and now some varieties with relatively strong lodging resistance and relatively high yield are selected for direct seeding. Therefore, new rice varieties should be bred for direct seeding. Liu et al.[94] reported a new internode dwarf with a rice lodging resistance gene that provided a way to study dwarf varieties suitable for rice direct seeding.

5.2 Rice seed treatment

The seedling rate of rice direct seeding can be improved by proper seed treatment[95]. The general approach involves seed soaking, pre-germination, and coating[5,16,96-98]. Seeds need about 24 h to general soak and pre-germinate with temperature controlled at about 25°C. Studies have shown that seed soaking with a certain concentration of salt solutions such as KCl, NaCl, or $CaCl_2$ is beneficial to rice germination[99-103]. Drying can improve the seed germination rate by more than 20% and reduce the germination time to 1-3 days[16]. Japan and South Korea applied iron and calcium oxide coatings and oxidation treatment to seeds to control the precision hill-drop sowing rate. Coated seeds can prevent harm to birds. Furthermore, coated seeds are more than 50% heavier, and this can prevent drifting in RWDS[104,105]. However, seed coating has a high cost, and it delays germination by 1-3 days.

The seed treatment of different direct seeding methods is also different. Dry seeding is usually used in rice direct seeding. Dry seeds, wet seeds, or buds can be used with RWDS[16]. The coated seeds are treated in different ways and are suitable for various direct seeding methods[5].

5.3 Chemical weed control in paddy field

Weeds compete with crops for nutrients, space, sunlight, and water, and affect crop growth and yield. Rice direct seeding was more difficult to control weeds than transplanting, because there is no water layer to control weeds in the field[106], and weeds and rice seeds germinated at almost the same time when direct seeding was performed. An American study transcribed antidrug genes into rice genes to produce strong resistance variety, then targeted chemical herbicides were used to control weeds damage. However, weeds also showed resistance after a few years. In general, early weed control involves deep- ploughing the soil. Deep-ploughing can bury shallow weed seeds deep into the soil; however, it may also turn deep weed seeds to the surface[16]. Rotation and intercropping can also be performed and combined with suitable herbicides. Wang[99] conducted a study that spraying Pretilachlor (herbicide) on the third day after sowing, and carried out better weeding effect, little effect on the germination of seeds and the grain yield in Southern China.

6 Application of precision rice water direct seeding in China

6.1 Trends

PRHDD with synchronous furrowing and ridging has been popularized and used in 26 Chinese provinces including in Southern China, Southwest China, Yangtze River region, Northeast China, and Northwest China as well as in Thailand, Laos, Burma, Vietnam, and Italy since 2006. Hill-drop drilling technology can meet rice planting requirements under different temperature conditions and planting habits with suitable sowing density (row/hill spacing and seeding rate) and cultivation technology. With technological development, the use of hill-drop drilling for wet paddy has increased rapidly in China, especially in the middle and lower reaches of the Yangtze River region (e.g., Shanghai, Zhejiang, and Anhui). PRHDD technology is extremely suitable for single-cropping rice because of suitable climatic conditions, suitable growth period, suitable varieties of rice, high level of agricultural mechanization, easy acceptance of planting habits, and management departments. Figure 16 shows the trend of precision rice seeding in China since 2006.

6.2 Rice production costs

China has a large rice planting area, and rice planting methods are different in each area. Common rice planting methods currently include mechanical transplanting, mechanical throw-planting, mechanical drilling, mechanical hill-drop drilling, manual transplanting, manual throw-planting, and manual sowing. The proportion of areas with manual transplanting and mechanical transplanting is large. However, considering the labour shortage and high production cost, farmers are increasingly switching to manual sowing and mechanical drilling. In recent years, the area

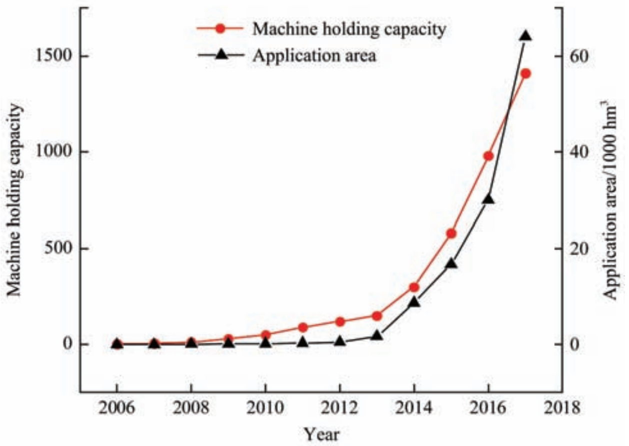


Figure 16 Development trend of machine holding capacity and application area

by mechanized direct seeding has been increasing. PRHDD can be popularized and applied in consideration of its technology feasibility and yield impact as well as its labour intensity and production cost. Therefore, this study identified the advantages of PRHDD from the viewpoint of production efficiency.

(1) Research method

This study investigated the production costs of different rice planting patterns in 15 provinces in China and conducted a comparative analysis of the economic benefits. The rice production cost mainly includes the following aspects: land, tillage, sowing and transplanting (seeding/seedling), agricultural costs (seeds, fertilizers, pesticides, herbicides, etc.), field management, and harvesting.

The total production cost can be calculated as total production cost: $C_n = C_1$ (cultivated land) + C_2 (sowing) + C_3 (transplanting) + C_4 (agricultural costs) + C_5 (harvesting) + C_6 (other costs)

where, the sowing cost is divided into direct seeding C_{21} and seedling C_{22}, and the agricultural cost is divided into seed C_{41}, fertilizer C_{42}, pesticide C_{43}, and herbicide C_{44}. The lease fee C_0 differs greatly across different areas, so it is not considered in the total production cost.

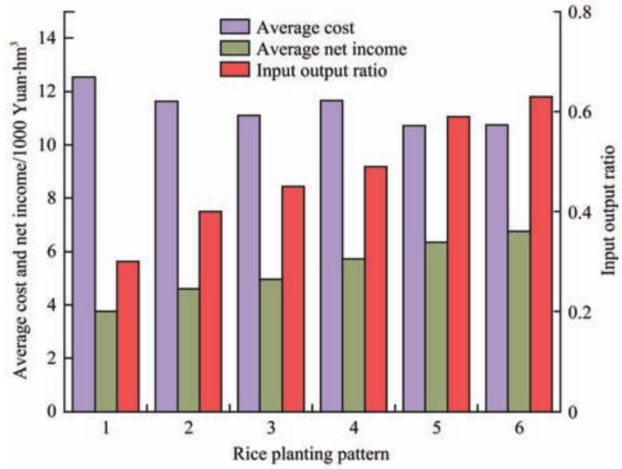
The average production cost and average net income of various types of rice planting methods in China can be calculated from the survey data. The "input-output ratio" is used to compare the economic benefits of different technologies. This ratio expresses the unit production or output for 1 unit of investment. It can be expressed in the form 1:N, where the higher the N value, the greater is the economic benefit.

(2) Economic benefit analysis results of different rice planting methods

Figure 17 shows the comparison results of the economic benefits of different rice planting methods. The input-output ratio (1:N) of different rice planting methods decreases in the order of mechanical PRHDD, mechanical drilling, manual seeding, mechanical transplanting, and manual throw-planting. Compared with manual transplanting, manual throw-planting, manual seeding, mechanical transplanting, and mechanical drilling, the average net income of mechanized rice planting is higher by 80%, 46.6%, 36%, 18.1%, and 6.1%, respectively. Rice direct seeding thus clearly affords a large economic benefit.

6.3 Rice yield

Rice yield is an important technical index for evaluating advanced rice planting technologies. Table 2 shows production records for various areas in China. PRHDD showed rice yield exceeding 9 t/hm^2, whereas the conventional rice yield was about 8 t/hm^2. Compared with manual sowing in the same area, the average yield was increased by 16.7%. The overall average rice yield of PRHDD technology was up to 8.8 t/hm^2, which exceeded China's average rice production level of 6.4 t/hm^2 (National Statistical Bureau, 2013–2016). Therefore, application of RWDS technology in suitable areas can result in stable and high yields of rice.



Note: In x axis, 1-6 respectively indicate Manual transplanting, Manual seedling throwing, Manual broadcasting, Mechanical transplanting, Mechanical line sowing, Mechanical hill-drop drilling.

Figure 17 Economic benefits of different rice planting patterns

Table 2 Rice yield of rice hill-drop drilling machine in some regions of China

Province	Year	Rice varieties	Yield/t·hm^{-2}
Xinjiang	2015	Xindao36#	10.5
Heilongjiang	2015	Longdao5	9.2
	2017	Longjing21	9.2
Shanxi	2014	Huanghuazhan	10.7
	2015	Huanghuazhan	12.2
Sichuan	2014	Dexiang4103	9.6
		Huanghuazhan	9.5
	2015	Jing3You177	11.8
		Huanghuazhan	11.5
		Chuanyou6203	9.5
		Jingyou127	10.1
		Jingnei5You37	9.6
	2017	Quanyouhuazhan	12.5
Zhejiang	2013	Chunyou84	12.3
	2014	Chunyou 84	12.5
	2015	Chunyou 927	12.9
Shanghai	2013	Xiushui134	9.4
	2014	Xiushui134	9.5
	2015	Huayou14	12
Jiangxi	2014	Zhongjiazao17	8.7
	2015	Zhuliangyou819	8.4
	2016	Heshengliangyou1#	8.3

7 Conclusions and prospects

7.1 Conclusions

Compared with other mechanized rice planting techniques, PRHDD with synchronous furrowing and ridging affords obvious advantages and conforms to the scientific concept of combining agricultural machinery and agronomy. It affords significant advantages in terms of rice yield, economic benefit, and resource saving by saving time, labour, and cost and increasing efficiency. PRHDD with synchronous furrowing and ridging is therefore being used increasingly in China, and it finds broad application prospects owing to the Chinese government's policy of promoting the development of mechanized rice planting.

7.2 Prospects

(1) Natural conditions and cropping systems differ greatly between China and the rest of the world. Therefore, when adopting advanced foreign technologies, direct seeding equipment tailored to Chinese conditions should be developed to achieve increased mechanization of rice direct seeding. PRHDD with synchronous furrowing and ridging technology is a scientific planting mode that has been verified to be compatible with the basic conditions in China.

(2) The rapider development, wider application scale and scope of precision rice hill-drop drilling technology and equipment has attracted more and more agricultural machinery manufacturing companies' (Kubota, Yanmar etc) interest. For example, in China, 30% of the rice planting area is expected to adopt mechanized direct seeding, which indicates the wide application prospect of precision rice hill-drop drilling technology.

(3) More attention should be paid on the key technologies of the precision rice hill-drop drilling technology, including the metering device and the overall structure of machine. The metering device should be able to adapt to the sowing rate requirements of different rice varieties and maintain accuracy at high speed. The light-weight overall structure and automatic control system (including automatic profiling, seeding quality monitoring) should be designed.

(4) The emphasis of popularization and application of precision rice hill-drop drilling technology is, the combination of agricultural machinery and agronomy, including safe and efficient weeds control, seedling rate protection measures, high yield and quality measures, and so on.

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