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Research Paper

Development and performance evaluation of a wet-resistant strip-till seeder for sowing wheat following rice

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Seedling establishment is critical for grain yield and net benefits of wheat in wet clay soil after puddled rice harvest in the Yangtze River basin (YRB) of China. A wet-resistant rotary strip-till seeder (WR seeder) was developed to drill seeds in zero tillage (ZT) conditions with complete rice residue mulching. The rotary blades adopted were medium radius C type blades creating a 50–60 mm wide and 30–50 mm deep furrow for seed placement. The pressing roller, usually used in the traditional wheat seeders, has been replaced by two ground wheels covered in rubber to reduce the mud adhesion. Moreover, a stainless-steel chain was installed behind the machine for better seed covering with soil. Based on three-year long field comparisons with the traditional deep tillage seeder (DT seeder) and a rototiller disc-type seeder with shallow tillage (SHT seeder), the six-row WR seeder significantly enhanced seedling establishment, and reduced energy consumption by 51.3% and 24.5%, respectively. The WR seeder also conserved the topsoil moisture. Over three years, the WR seeder produced similar grain yield to the SHT seeder, but 3.1% more than the DT seeder. Moreover, the net profit with WR seeder increased by 39.4% and 0.9% compared to the DT and SHT seeders, respectively. Furthermore, comparisons across the YRB also confirmed the positive effects of the WR seeder on grain yield and economic benefits over the conventional seeding practices. Thus, it was demonstrated that the improved seeder is an optimal option to enhance the RW system productivity in the YRB.

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Nomenclature

CNY	Chinese yuan
CV	Coefficient of variation (%)
DM	Dry matter (Mg ha^{-1})
DT	Deep tillage
EFC	Effective field capacity (ha h^{-1})
HI	Harvest index
k	Actually utilised machine width ratio (%)
PTAFL	Proportion of tiller appearance in the first leaf axil
RW	Rice-wheat
S	Machine travelling speed (km h^{-1})
SER	Seedling emergence rate (%)
SCR	Seed cover rate (%)
SHT	Shallow tillage
SMR	Seedling missing rate (%)
IGP	Indo-Gangetic alluvial plain
T_e	Effective operating time (h ha^{-1})
T_h	Time loss during headland turning, seed/fertiliser box refilling, small adjustments, etc. (h ha^{-1})
T_0	Theoretical time calculated based on machine width and traveling speed in ideal conditions (h ha^{-1})
W	Rated machine width (m)
WR	Wet resistant
YRB	Yangtze River basin
ZT	Zero tillage
η	Actual field efficiency (%)

1. Introduction

In the rice-based cropping system in the Yangtze River basin (YRB) of South China, wheat is the predominant winter crop in rotation with summer paddy rice (rice-wheat (RW) system). Intensive tillage after rice harvest to establish the winter wheat crop has been the standard practice for decades in the YRB (Ding et al., 2020). However, due to the high residual soil moisture content following paddy rice and abundant autumn rainfall, timely land preparation and wheat sowing are challenging when the conventional farming practices utilizing available machinery are adopted (Wang et al., 2009; Zhang, Yao, Tang, Chen, & Yan, 2020). Seedling establishment in previously puddled, wet clay soils is one of the most critical factors in determining wheat grain yield, end-use quality traits, and net economic benefit (Bohra & Kumar, 2015).

Numerous researchers have demonstrated the potential economic and environmental benefits of cultivating wheat with minimum soil disturbance, including timely crop establishment, reduced establishment costs, less waterlogging stress, and increased grain yield and nutrient use efficiency in comparison with conventional tillage (Gupta, Naresh, Hobbs, Zheng, & Ladha, 2003; Jat et al., 2014; Somasundaram et al., 2020). Accordingly, minimum and zero tillage (ZT) practices for wheat establishment after rice harvest in the YRB have been explored and developed since the 1980s (Wang et al., 2009; Zheng, Chi, Jiang, Tang, & Zhang, 2010). ZT wheat sowing was performed manually in those early days, where seeds were placed in holes or furrows dug by hand and covered with farmyard compost. During the 1990s, a small hand-drawn two-row seeder improved the ZT practice by dropping wheat seeds on the moist soil surface, which were then covered manually with previous rice residue (Fig. A1a and A1b). However, in the initial stages of ZT, rice residue was removed after harvesting, leaving the soil surface clean for the wheat sowing operation. Unfortunately, with the shortage of rural labour in the early 2000s, rice residue could not be managed effectively after harvesting. On the other hand, the rural residential energy transition decreased the consumption of crop residue by 51% from 1992 to 2012 in China (Tao et al., 2018). Moreover, large-scale intensive systems gradually replaced the traditional free-range systems for livestock production, and the former prefer industry-processed feed rather than crop straw (Kang et al., 2016). Thus, crop residue became a significant burden, which led to widespread open-field burning.

RW regions in South Asia experienced similar issues (Matin, Hossain, Gathala, Timsina, & Krupnik, 2021; Sidhu et al., 2007, 2015), where the constraints of direct drilling of wheat seeds into heavy rice straw were addressed in the early 2000s by the introduction of the Happy Seeder (Sidhu et al., 2007). The earlier versions of Happy Seeder comprised a flail mower and seeding devices that chopped and lifted the residue over the entire seeding unit. The subsequent improvements (Combo Happy Seeder and Turbo Happy Seeder) included individual flails rotating in front of the seeding tines clearing the residue in narrow strips to facilitate the seeding operation (Sidhu et al., 2015). In the absence of intensive land preparation, operational costs decreased significantly with the use of Happy Seeder for ZT wheat sowing. In 2014, a similar ZT wheat seeder based on Turbo Happy Seeder design was adopted in the upper YRB. Nevertheless, despite high expectations, the operation of the machine faced many challenges due to high soil moisture and heavy residue retention (>8 Mg ha^{-1}) (Fig. A2a). The space between sowing tines was severely reduced by wet residue, and the rotor flails failed to function (Fig. A2b). In contrast, according to Matin et al. (2021), a rotary strip-till seeder can intensify rainfed rice-based cropping systems and achieve the target grain yield and environmental benefits. Considerable effort was devoted to improving the strip-till seeder key components, such as the rotary blade, shape and layout of the rotor shaft (Matin, Fielke, & Desbiolles, 2014, 2015, 2021). Even so, these improved seeders were tested only in optimal soil moisture conditions, and their performance under wet soil conditions was not evaluated.

A six-row (spacing 250 mm) strip-till seeder, pulled by a full tracked tractor, was designed and produced in 2015 in China. These seeders consisted of a seeding and fertilisation device installed on the top of a rotavator with a reduced total number of blades, leaving four blades per mounting flange to create seed furrows in front of each seed tube. In addition, fertiliser tubes were set in front of the rotary strip-till blades. The fertiliser was dropped and incorporated by the strip-till blades, and seeds were dispensed from the seed tubes into the bottom of the furrows created by strip-till blades. The rotavator housing captured and deflected soil back to the soil surface for seed covering. However, these seeders had minimal residue handling capability in postharvest rice field conditions. In general, the Chinese harvesters are not fitted with choppers and spreaders at the rear of the machine for even distribution of crop residues across the width of the machine header, which can exacerbate residue blockages in the following seeders. In most cases, the previous strip-till seeder performed well on wet fields with less residue retention due to its light weight and a row spacing of 250 mm between the strip-till units. However, the commercial rotary tiller blades (bent C blade) were strongly curved causing much disturbance to the soil surface across the width of the machines. Furthermore, if the crop residue was wet, not distributed uniformly, or not managed correctly, mud and residue accumulated in the rotary unit causing blockages and limiting crop establishment.

To overcome residue and soil challenges during seeding, a wet-resistant (WR) strip-till wheat seeder was developed that can perform well under wet clay soil conditions and wet and heavy rice residue loads (>8 Mg ha^{-1}). Effective residue processing and narrow strip tillage in front of the planting tines were essential in reducing the wet rice stubble blockage and creating adequate seeding slot backfilling to improve soil-seed contact for better seedling establishment. Additional aids were required at the back of the machine to enhance seed coverage without generating mud and straw blockages. This paper describes the development of the WR strip-till seeder and evaluates its performance in terms of crop establishment, grain yield, incomes, and energy consumption. The original, partially modified six-row WR seeder was evaluated at an experimental station and compared to the conventional seeders. An improved version was then evaluated under variable residue retention conditions. Furthermore, on-farm comparisons of improved seeders with different configurations (eight, 10 and 12 rows) were conducted with various conventional tillage and seeding practices prevailing across the YRB region.

2. Materials and methods

2.1. Wet-resistant seeder development

To make the strip-till seeder suitable for wet clay fields required several iterations of blade shape, seeding tubes, row spacing, and seed covering devices, which produced several versions with a similar function.

2.1.1. Improvements to rotary-tiller blades

A set of four blades are installed on each mounting flange and two adjacent blades 180° out of phase for creating seedbed furrow (Fig. 1a). The number of blade sets depends on the length of the rotating shaft and the actual sowing needs. In the YRB, the conventional large radius C type blades with 50 mm width and 225 mm turning radius are widely adopted (Fig. 2a). This type of blade creates a furrow width of more than 100 mm, disturbing more than 50% of the topsoil across the width of the machine. However, the blades and rotor are easily wrapped in straw, resulting in inefficient chopping. Therefore, the width of the sidelong section of the blades was reduced to 27 mm, producing what was called the medium radius C type blades (Fig. 2b). The turning radius of improved blades was 225 mm and the diameter of matched shaft was 84 mm, resulting in a rotation with a 534 mm diameter. After the improvement, the blades created a 50–60 mm wide and 30–50 mm deep furrow. Consequently, the soil between blade sets remained undisturbed and only less than 30% of topsoil was disturbed. In practice, the forward speed of the tractor was about 3.5 km h^{-1} and the speed ratio increased from the conventional 265/760 to 390/760 for a higher rotary speed. The mixture of straw and mud attached to the blades was easily shed off by the increased centrifugal force during seeding.

Moreover, the rubber mud guard was mounted behind the seed tubes for capturing clods created by blades (Fig. 1b). The advantages of rubber mudguard are as follows: firstly, a portion of the thrown mud can be redirected to cover seeds, because it returned to the ground latter than seeds; secondly, the softness of the rubber cover prevents mud adhesion in wet fields and reduce the possibility of mud blockages.

2.1.2. Modifications to seed tubes

The seed dropper tubes (Fig. 1b) operated without a leading tine and were arranged close to the rotary blades. After a furrow was created by blades, the seeds would freely fall into the fresh furrow. In actual operation, the outlet of the tube was kept at a certain distance from the soil surface to avoid mud adhesion. Furthermore, they were slightly narrowed and mounted rearward facing to prevent the pipe orifice from being clogged with mud. However, because the leading tine was not connected to the seed tube for furrow opening, some seeds did not fall accurately into the intended position in the furrows created by blades.

2.1.3. Improvements to ground wheel

A common component in Chinese seeding machines is a ground roller, which serves several functions: equipment support and depth adjustment, drive for the fertiliser and seed metering device, and press wheel to facilitate soil-to-seed contact. However, the standard press roller quickly gathers mud and residue from the newly created furrows. Thus, its drive wheel and seed pressing functions are inadequate. The roller was replaced with two rubber-covered star wheels to shed mud, which were mounted at either end of the shaft. The adhesion between the rubber surface and mud thrown by blades was relatively low, thus the mud easily fell during seeding, which substantially improved the adaptability of the seeder to wet fields (Fig. 1c, Fig. 3 and Video A1).

Supplementary video related to this article can be found at https://doi.org/10.1016/j.biosystemseng.2022.05.019

2.1.4. Stainless steel chain as seed-covering device

The key to seedling establishment with a strip-till seeder is to ensure seeds are placed in a furrow and adequately covered with soil. However, backfilling is limited in high soil moisture conditions due to the formation of large wet clods, which largely remain on the soil surface between the rows. A

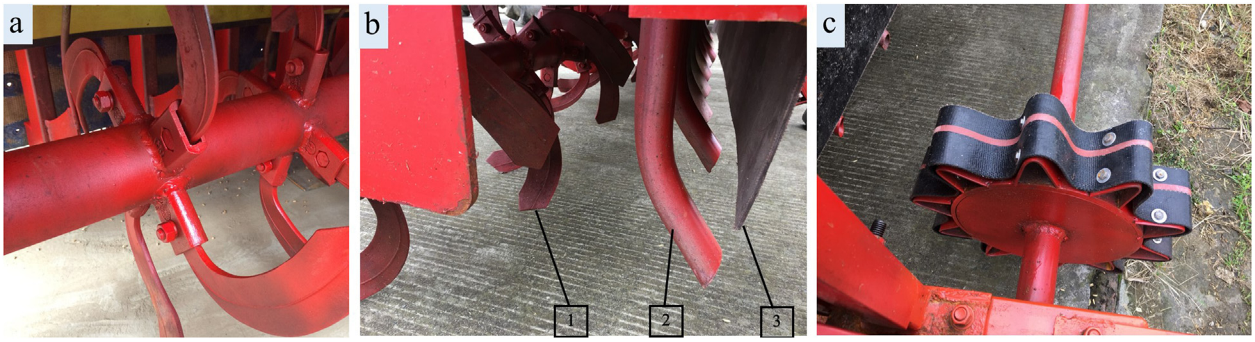

Fig. 1 – Improvements to key WR seeder components: (a) Set of four blades installed on each mounting flange for creating seedbed furrow; (b) Modified rear-facing seed tube without leading tine to prevent pipe orifice from mud clogged: 1. medium radius C type blade; 2. seed tube; 3. rubber mud guard; (c) Press roller replaced with two improved rubber-covered ground wheels fitted to shaft outer end.

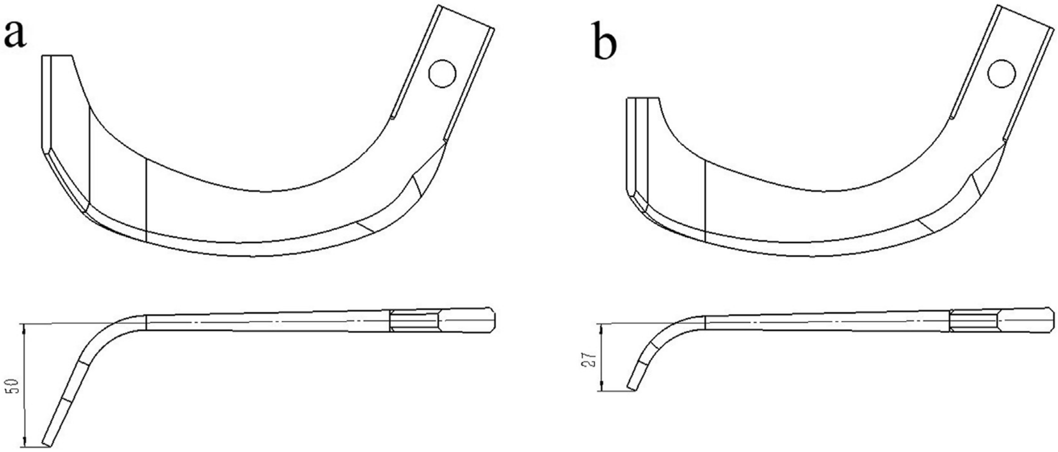

Fig. 2 – C type blades: (a) Conventional large radius C blade; (b) Improved C type blade with reduced radius.

stainless steel chain was attached behind the machine to sweep the clods and residue into the furrow to increase backfill without generating choking and mud or residue build up (Fig. 4 and Video A1).

2.1.5. *Configuration of WR seeders*

A wet-resistant strip-till seeder was created to operate in wet clay soil with residue retention by combining all the above improvements and modifications. The primary differences between the various WR seeder versions were the number of rows, width, and power requirements (Table A1).

2.2. *Experimental design for field evaluation of various WR seeders*

To optimise the WR strip-till seeder, a series of field evaluations were conducted on various machine configurations at an experimental station and on actual farms. The controlled experiments compared conventional seeders with a partially modified six-row WR strip-till seeder. Furthermore, the adaptability to different residue retention conditions of a 10-row WR strip-till seeder was evaluated. The extensive on-farm trials compared the improved WR strip-till seeders with a variety of conventional tillage and seeding practices on the same or adjacent fields in three provinces across the YRB (Table A2).

2.2.1. *Comparison of six-row WR strip-till seeder to conventional seeders at experimental agricultural station*

2.2.1.1. Experimental site. Comparison tests of three seeders, namely a six-row partially modified WR strip-till seeder, a conventional seeder operated after intensive deep tillage (DT, tillage depth 180–200 mm, Fig. A3a), and a rototiller disc-type seeder with shallow tillage (SHT, Fig. A3b) were conducted over three consecutive wheat growing seasons between 2016 and 2019 at the Sichuan Academy of Agricultural Science Experiment Station (104°39′N, 31°00′E), located in Guanghan, Sichuan Province, in the upper YRB of Southwest China. The partially modified WR strip-till seeder used in the comparisons was an earlier version, which incorporated all the improvements described previously except the two rubber-covered star wheels, which were replaced by a light press roller.

The soil in the station had a clay loam texture based on the American soil texture classification standard (USDA, 1999). The saturated moisture content of the topsoil in the test field was approximately 40%; other soil physicochemical properties before wheat sowing are shown in Table A3. The previous

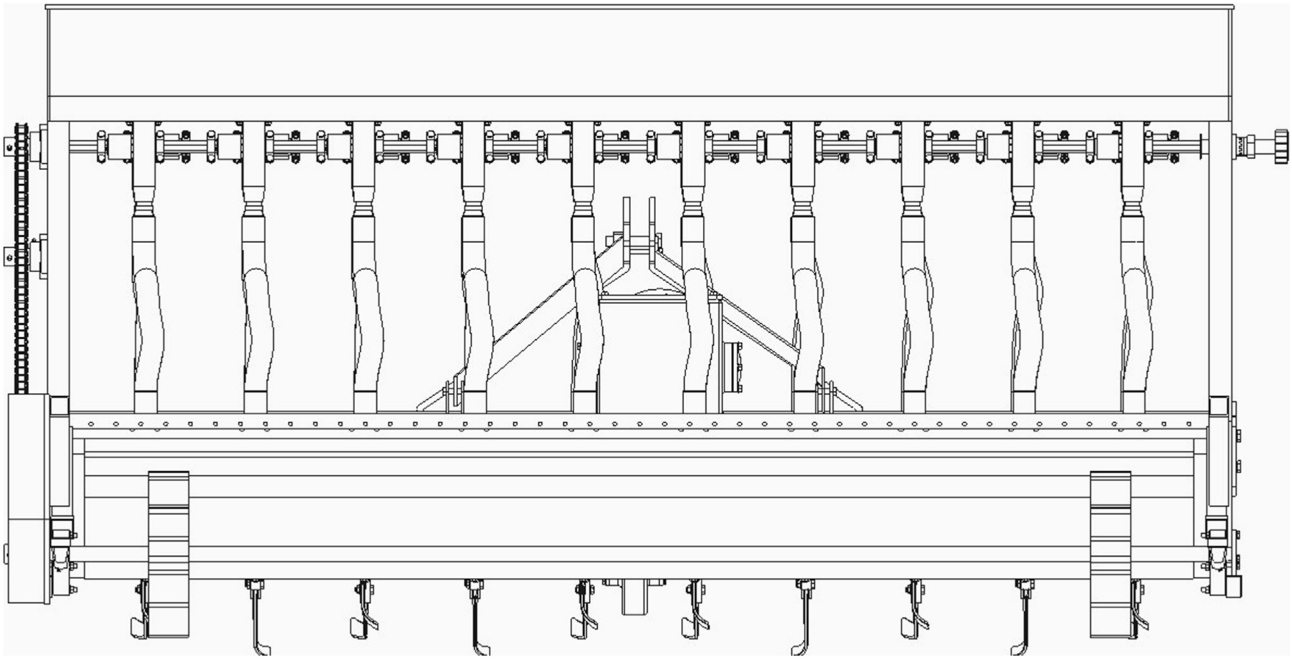

Fig. 3 – 10-row WR seeder rear view.

Fig. 4 – WR seeder operating in wet field with heavy rice straw retention with stainless steel chain installed behind for seed covering.

rice crop was machine transplanted in late-May and harvested on September 20th, October 5th and October 5th in three tested years, respectively. After harvest, the rice straw and stubble was crushed using a straw mulcher. Daily mean temperature and precipitation from October to mid-May in the three consecutive wheat seasons from 2016 to 2019 are shown in Fig. A4.

The experimental site was 0.35 ha and was divided into three treatments, i.e., three seeder types or planting methods. Each machine operating area was 38 m × 10 m in three repetitions. The previous rice crop was harvested using a full-feed combined harvester, and the residue was left on the ground in windrows behind the harvester. The stubble and residue were mulched with a flail mower in a separate operation. Machinery characteristics, agronomic operations, and timelines for each seeder type are outlined in Table A4.

The DT seeder plots were rotary tilled twice while incorporating the mulched residue before seeding operations. Before and after sowing, mechanical compaction was applied for levelling and increasing soil-seed contact using a small roller leveller. In contrast, the shallow-tillage seeder (SHT seeder, tillage depth 50–70 mm) and the WR seeder were operated under ZT conditions. The site was fertilised with 150 kg N ha^{-1} in two rounds with 60% as basal and 40% as top-dressing. The basal compound fertiliser (N:P:K = 15:15:15) was applied at a rate of 600 kg ha^{-1}, and an additional 130 kg ha^{-1} urea was top-dressed by hand at the wheat stem elongation stage after adequate rainfall. The basal fertiliser was broadcast before the second rotary tillage in DT plots, while it was applied at sowing time by the seeder in the other two treatments. Some of the operations (tillage and sowing) were delayed due to high soil moisture in the last two years. The trials were only rain-fed without additional irrigation, and weeds, diseases, and pests were appropriately managed with relevant chemicals at the optimal time in all three years.

The theoretical seeding rates for the three seeders were kept at the same level by calibration carried out before sowing. However, due to the coarse deep tillage and higher soil moisture in the last two years, large amount of mud adhered to the ground wheel of the DT seeder, resulting in a higher actual seeding rate than the theoretical value. To avoid the impact of variable sowing rates, two 15 m^2 quadrats (referred to as Q_1 and Q_2) were fixed in each plot after the seedling emergence investigation. The initial seedling emergence was maintained at the same level for the three treatments by removing manually redundant seedlings within the quadrats. One quadrat (Q_1) in each plot was used to determine the grain yield and yield components, and the other (Q_2) was used to investigate the changes in soil moisture during the wheat growth period.

2.2.1.2. *Sampling*

2.2.1.2.1. *Seedling and crop establishment*. Following planting, the seed depth was assessed in two random sampling locations in each plot, each with 10 sample points. In the WR seeder plots, the sowing depth was taken as the distance from the bottom of the seed to the surface of inter-row ZT soil. For the DT seeder and SHT seeder, seed depth was measured from the bottom of the seed to the level soil surface. In addition, five quadrats (five 1-m long rows) were randomly selected in each plot to record the number of uncovered seed in the 2017/2018 and 2018/2019 wheat seasons. The seed cover rate (SCR) was determined from the following formula:

SCR (%) = (total number of seeds in selected quadrat −uncovered seed number) / total number of seeds in selected quadrat × 100%, where the total number of seeds in a quadrat was estimated from the seeding rate and seed weight.

After emergence, two randomly placed quadrats in each plot, covering five 1-m long rows, were used to assess the seedling emergence rate (SER) depending on the applicable sowing rate as follows (Du & Tuong, 2002):

SER (%) = total number of seedlings in a quadrat / total number of seeds in a quadrat × 100%.

Generally, the seeds continued to fall during the normal seeding operation for the three seeders. However, stands loss often occurs in the field due to several reasons, including no seeds falling because the ground wheel or roller does not roll, the mouth of the seed tube is blocked, or ineffective coverage. In this study, the reason for seedling missing could not be determined. Furthermore, there was no clear opinion on the specific criterion for assessing seedling missing. In the conventional practice of hole-seeding in the upper YRB, the distance between holes in a row is 100 mm. From this experience, if there were no seedlings in a 200-mm long stretch of sowing row, we declared this location as a missing point. The total length of all missing points was defined as the length of seedling missing in a quadrat. The seedling missing rate (SMR) for a given quadrat was calculated as follows:

SMR (%) = row length of seedling missing in a quadrat / total length of wheat rows investigated in a quadrat × 100%.

The uniformity of seedling distribution is another important characteristic to evaluate field management. The common indicator to access the field seedling uniformity is the coefficient of variation (CV) of seedling distribution (Liu et al., 2017). The CV of seedling distribution was calculated from the standard deviations of the investigated two quadrats divided by the average number of seedlings in two quadrats for each plot.

At the peak tillering (40–45 days after sowing), approximately 50 wheat shoots from Q_2 in each plot were collected to assess the number of stems per plant, foliar age of the main stem, and the proportion of the tiller appearance in the axil of the first leaf (PTAFL) in main stems. The mean value of the samples from each plot was used to determine the quality of seedling growth in the plot.

2.2.1.2.2. *Grain yield and yield components*. The number of premature fertile spikes was assessed from two sampling points in quadrat Q_1 along the diagonal. Each sampling point covered five 1-m long rows. About 50 representative aboveground shoots were collected from quadrat Q_1 to investigate the grain numbers per spike. Following grain threshing, samples were dried at 70 °C to constant weight. Harvest index (HI) was calculated from the sample dry grain weight/total dry matter (DM) (Donald & Hamblin, 1976). The remaining plants in quadrat Q_1 were harvested and threshed manually, the grains were weighed, and grain moisture was determined using a PM-8188-grain moisture meter. The grain yield was reported at 13% moisture, and the total aboveground DM at maturity was determined from the dry grain yield/HI (Kemanina, Stöckle, Huggins, & Viega, 2007).

2.2.1.2.3. *Soil moisture*. In the upper YRB, the rainfall is much smaller in winter. The water stored in the root zone is particularly important for plant growth. According to Fan, McConkey, Wang, and Janzen (2016), 50% of roots can be found in the upper 200 mm layer of soil for all crops. Therefore, soil samples from the 200 mm deep upper layer were collected before sowing and during the wheat growth period to assess soil moisture status.

Before soil tillage for the DT seeder practice, four random soil samples of the top 200 mm deep soil layer were collected from the whole field and dried at 70 °C to a constant weight for soil moisture determination. After wheat seeding, the soil moisture content next to sowing rows was monitored continuously for seven days, and two samples were randomly selected from each plot and mixed equally for drying (70 °C) and weighing. Two random soil samples from inter-rows in quadrats Q_2 were also collected for moisture monitoring at wheat sowing, shoot elongation, anthesis, and middle grain-filling stage. Soil organic matter (SOC) was relatively high in the tested field (approximately 50.0 g kg^{-1}). To prevent the decomposition of soil organic matter, we adopted a drying temperature of 70 °C instead of the conventional 105 °C (Lekshmi, Singh, & Baghini, 2014).

2.2.1.2.4. *Energy consumption*. The energy consumption for wheat sowing was calculated based on the direct (diesel fuel) and indirect energy consumption (energy embodied in machinery). The direct energy consumption was calculated using the method and reference information described in Sidhu et al. (2015) as a function of fuel consumption, energy equivalent (MJ L^{-1}), and effective field capacity. The effective field capacity (EFC, ha h^{-1}) was required for assessing each machinery operation using the method provided by Sidhu et al. (2015). It is a function of the rated equipment width, forward speed, and total field time losses during the operation (including headland turning, seed/fertiliser box refilling, small adjustments, etc.):

$$EFC = S \times W \times \eta/10 \quad (1)$$

where.

S = machine travelling speed (km h^{-1})
W = machine rated width (m)
η = actual field efficiency (%)

$$\eta = T_0/(T_e + T_h) \times 100\% \quad (2)$$

T_0 = theoretical time calculated based on machine width and traveling speed in ideal conditions (h ha^{-1})

$$T_e = \text{effective operating time (h ha}^{-1}) = T_0 \times 100 \times k \quad (3)$$

k = actually utilised machine width ratio (%)
T_h = time lost during headland turning, seed/fertiliser box refilling, small adjustments, etc (h ha^{-1}).

The fuel energy was calculated as follows,

$$\text{Fuel energy (MJ ha}^{-1}) = \text{fuel consumption (L h}^{-1}) \times \text{energy equivalent (MJ L}^{-1})/\text{effective field capacity (ha h}^{-1}) \quad (4)$$

For calculating the energy embodied in machinery, the following formula was used:

$$\text{Machinery energy (MJ ha}^{-1}) = \text{weight of machine (kg)} \times \text{energy equivalent (MJ kg}^{-1}) / [\text{wear-out life (h)} \times \text{effective field capacity (ha h}^{-1})] \quad (5)$$

The operations and parameters considered for calculating the energy consumption for different sowing practices are listed in Table A5. The energy equivalents for the diesel fuel, tractor, and seeders were taken as 1.96 MJ L^{-1}, 64.8 MJ kg^{-1} and 62.7 MJ kg^{-1}, respectively (Sidhu et al., 2015).

2.2.1.2.5. *Costs and economic benefit*. All costs (seeds, fertiliser, pesticides, machinery rental, and labour costs) were expressed in Chinese Yuan (CNY). The machinery rental cost was calculated using the local service provider prices, and included mechanised rice residue management, soil tillage, sowing, and harvesting. In addition to land preparation, sowing and harvesting, top-dressing and spraying were performed manually. The output was based on grain yield and the averaged unit price of 2.4 CNY kg^{-1}. The average daily rate for labour in the YRB was taken as 80 CNY. The economic benefit of each planting practice was based on the net income determined from the difference between the outputs and costs.

2.2.2. *Evaluation of improved 10-row WR strip-till seeder under different residue managements*

In the 2019/2020 wheat season, a residue retention test was carried out on three adjacent 0.2-ha fields at the experimental station to assess the improved 10-row WR strip-till seeder performance. Each field was treated as one treatment and divided into five subplots of equal size to assess seedling establishment. In Treatment 1 (original status), rice residue was unevenly spread on the soil surface after harvesting with a full-feed combine-harvester, while 400 mm standing stubble was left in the field. In Treatment 2 (chopped), a half-feed combine harvester harvested rice, while stems were chopped by the harvester into 60–80 mm lengths and evenly dispersed. In Treatment 3 (mulched), following harvesting with a full-feed combine harvester, all standing stubbles and residue were mulched with a flail mower. During seeding process, the other operational parameters of the seeder were unchanged. Seedling establishment and grain yield were determined in each subplot as described in section 2.2.1.2.

2.2.3. *On-farm comparisons of improved 8/10/12-row WR strip-till seeders with conventional tillage and seeding practices*

The WR seeders with various row configurations were introduced to farmers in three provinces in the YRB. A total of 23 participatory on-farm experiments in 18 locations were carried out from 2017 to assess the performance (grain yield and net income) of the improved WR strip-till seeder. These results were compared to various conventional tillage and seeding practices in field conditions. The comparisons were conducted in the same field or two adjacent fields. Wheat was planted from late October to early November. The participating conventional tillage and seeding practices varied across the provinces. However, except for soil preparation, sowing time, and planting method, the wheat variety and other agronomic management activities were similar for each comparison. Farmers conducted all the agronomic procedures according to their own arrangements. Detailed conventional operating procedures, soil texture, pre-sowing soil moisture (in the 200 mm deep upper layer) and total rainfall in October for each location are given in Table A2. The grain yield and yield components were measured at maturity, and all production inputs in each comparison were recorded to evaluate the net benefit.

2.3. *Data analysis*

Microsoft Excel 2013 was used for data processing, while IBM SPSS 22.0 was used for statistical data analysis (IBM, New York). The data were presented as averages. For the compared tests at the experimental station, the ANOVA *LSD* test was used to evaluate the significance of differences between treatments. For the on-farm comparisons, the statistical significance of differences was assessed using the paired t test.

3. Results

3.1. *On-station comparison of WR strip-till seeder with conventional seeders*

3.1.1. *Seedling establishment*

The sowing depth ranged from 24.1 mm to 49.1 mm over three years with an average of 37.3 mm for the WR seeder, which was significantly less than for the DT seeder at 43.3–57.3 mm, but not significantly different from the SHT seeder at 23.2–43.0 mm. However, under ZT conditions, the reduced flatness of soil surface due to mechanical compaction during rice harvest and uneven residue mulching resulted in higher variations in sowing depth for the WR seeder and the SHT seeder than for the DT seeder. Moreover, other seedling establishment parameters such as SCR were improved and seedling missing rate decreased for the WR seeder compared to the other two seeders, which resulted in increased seedling emergence rate and uniformity of seedling distribution in the field (less CV% of seedlings) for the WR seeder (Table 1).

Also, strong effects of treatment and interaction were observed on wheat agronomic properties at the peak tillering stage (Table 2). Across the three years, the SHT seeder treatment provided the largest tillering capacity with 2.57 tillers per plant, followed by the WR seeder (2.25), and the DT seeder (1.87). The foliar ages of the main stem were similar for the three seeder types. However, the averaged PTAFL in the WR and SHT seeder plots increased by 40.0% and 69.0% compared to the DT seeder, respectively.

3.1.2. *Grain yield and yield components*

The effect of sowing practices on grain yield and yield components varied amongst the three years. In the first and third year, all three seeders produced similar grain yield and biomass, while in the second year, the WR and SHT seeder treatments produced significantly higher grain yield than the DT seeder (improvements by 10.9% and 10.5%, respectively) (Table 3).

On average, the WR and SHT seeders significantly increased, by 15.8%–20.3%, the numbers of fertile spikes per m^2 compared to the DT seeder. Moreover, there was no significant difference in grain number per spike among the three treatments. The 1000-grain weight for the DT seeder was observably larger than for the other two seeders, but statistically different only in the first year.

3.1.3. *Soil moisture change*

The topsoil moisture was affected by the different seeder treatments (Fig. 5). Before soil tillage, the initial topsoil moisture ranged from 38.5% to 42.8% in the three years, which was close to or above saturation. Following deep tillage (DT treatment), soil moisture dropped rapidly in the pre-sowing period. The soil moisture with the WR seeder was on average larger during the entire wheat growth period compared to the DT seeder by 18.9%, 7.6%, and 23.7% in the three years, respectively. In most growth stages, the values for the SHT seeder were between those for the other two treatments.

3.1.4. *Energy consumption*

Due to without pre-sowing operations and less soil disturbance, the WR seeder treatments consumed 51.3% less energy than the DT seeder treatments (Table 4). However, the SHT seeder disturbed the entire width of soil surface and used more energy than the WR seeder.

3.1.5. *Costs and economic benefit*

Over the three years, the total costs for each treatment ranged from 9946 CNY ha^{-1} (WR seeder) to 11,781 CNY ha^{-1} (DT seeder) (Table 5). The net income in all three years using the WR seeder was on average 39.4% larger than that for the DT seeder. The net income using the SHT seeder was slightly less than for the WR seeder. Due to reduced costs and higher productivity, the cost-benefit ratio for the WR seeder exceeded 1.8, i.e., it was significantly larger than that for the DT seeder at 1.5.

3.2. *Evaluation of improved 10-row WR strip-till seeder in different residue conditions*

Under the original residue status, the average sowing depth was only 12.0 mm (Table 6), and many seeds fell on the residue with no soil contact. Consequently, the emergence was reduced, and the grain yield significantly decreased by 7.4% and 17.5% compared to the other two treatments, chopped and mulched, respectively.

3.3. *On-farm comparison of WR seeder to conventional practices across the YRB*

Across all the observations, the grain yields achieved with the WR seeder ranged from 4.9 Mg ha^{-1} to 8.3 Mg ha^{-1} with an average of 6.9 Mg ha^{-1} (Fig. 6). In contrast, the grain yields while using the conventional practices ranged from 3.6 Mg ha^{-1} to 7.9 Mg ha^{-1} with an average of 6.1 Mg ha^{-1}. Overall, in 20 out of 23 comparisons, the grain yields for the WR seeder were larger than for the conventional tillage and seeding. The fertile spike numbers increased significantly when the WR seeder was adopted in comparison to the conventional practices.

Table 1 – Wheat seedling establishment parameters under different sowing practices in wet clay soil with heavy rice residue retention.

Sowing machine	SER (%)	SCR (%)	SMR (%)	CV% of seedlings
DT seeder	75.2 (66.7–89.1)[a]	94.2 (88.8–99.6)	2.4 (0.4–4.3)	9.5 (5.1–14.3)
SHT seeder	79.0 (61.3–93.2)	94.2 (91.5–96.8)	4.7 (2.0–10.2)	6.9 (5.6–8.7)
WR seeder	80.6 (66.5–88.0)	97.1 (96.0–98.2)	1.3 (0.3–2.6)	5.9 (3.2–9.6)
F value				
Year		52.3***	2.8	0.4
Seeder		5.3*	0.6	0.5
Year × Seeder		8.8**	2.3	0.6

[a] Data averaged over three years with range shown in brackets. SER, Seedling emergence rate; SCR, seed coverage rate; SMR, seedling miss rate; CV, coefficient of variation.*** indicates statistically significant difference at $p < 0.001$,** at $p < 0.01$, and* at $p < 0.05$ using ANOVA test.

Table 2 – Wheat agronomic properties of individual plants at peak tillering under different sowing practices in wet clay soil with heavy rice residue retention.

Sowing machine	Stems per plant	Foliar age of main stem	PTAFL in main stems
DT seeder	1.87 (1.23–2.31)[a]	4.12 (3.50–4.60)	40.7 (15.4–78.0)
SHT seeder	2.57 (1.97–2.43)	4.29 (3.94–4.51)	69.6 (51.3–90.3)
WR seeder	2.25 (1.52–2.73)	4.17 (3.69–4.50)	57.0 (37.4–82.1)
F value			
Year	122.8***	111.7***	143.9***
Seeder	40.1***	4.8*	52.0***
Year × Seeder	7.3**	3.6*	10.6***

[a] Data averaged over three years and range shown in brackets. PTAFL, proportion of tiller appearance in the first leaf axil.*** indicates statistically significant differences at $p < 0.001$,** at $p < 0.01$, and* at $p < 0.05$ using ANOVA test.

Table 3 – Grain yield, biomass and yield components for different sowing practices in wet clay soil with heavy rice residue retention.

Year	Sowing machine	Grain yield (Mg ha^{-1})	Biomass (Mg ha^{-1})	Fertile spikes m^{-2}	Grain number per spike	1000-grain weight (g)
2016/2017	DT seeder	8.93 a	15.3 a	398 c	39.8 a	49.7 a
	SHT seeder	8.45 a	15.2 a	500 a	36.1 a	44.9 b
	WR seeder	8.93 a	15.7 a	456 b	37.7 a	48.3 ab
2017/2018	DT seeder	7.34 b	12.7 a	355 b	38.7 a	46.6 a
	SHT seeder	8.11 a	14.1 a	432 a	44.0 a	44.7 a
	WR seeder	8.14 a	14.3 a	451 a	38.9 a	43.6 a
2018/2019	DT seeder	6.04 a	10.4 a	312 a	42.9 a	45.1 a
	SHT seeder	6.52 a	11.7 a	349 a	37.3 a	43.9 a
	WR seeder	5.93 a	10. 8 a	326 a	38.3 a	44.1 a
Av.	DT seeder	7.44	12.8	355	40.5	47.1
	SHT seeder	7.69	13.6	427	39.1	44.5
	WR seeder	7.67	13.6	411	38.3	45.3

Values followed by different lowercase letters indicate significant differences between treatments for the same parameter in the same year using ANOVA *LSD* test ($p < 0.05$).

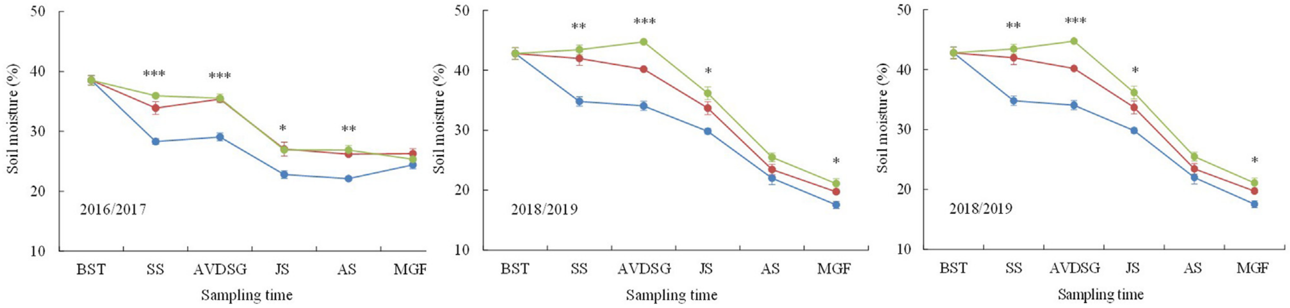

Fig. 5 – Changes in 200 mm deep topsoil moisture content from land preparation to wheat grain filling for different sowing practices in wet clay soil with heavy rice residue retention in three consecutive years (blue filled circles – DT seeder; red filled circles – SHT seeder; green filled circles – WR seeder). The error bars indicate standard deviation. * indicates statistically significant differences at $p < 0.001$, ** at $p < 0.01$, and * at $p < 0.05$ using ANOVA test. BST, before soil tillage; SS, sowing stage; AVDSG, average value during seed germination; JS, jointing stage; AS, anthesis stage; MGF, mid-grain filling stage. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)**

Moreover, the costs across the region for the conventional sowing practices were highly variable. Nevertheless, the costs when using the WR seeder were significantly reduced. The net income from utilising the WR seeders was significantly higher than that of local farmer practices at all sites, where the increases in net income ranged from 369 to 9179 CNY ha^{-1} with an average of 3109 CNY ha^{-1} (Fig. 6).

4. Discussion

Ineffective crop establishment constrained wheat production in the RW rotation system in the YRB of South China and the Indo-Gangetic alluvial plain (IGP) (Bohra & Kumar, 2015; Sidhu et al., 2015). The WR seeders described in this paper appear

Table 4 – Energy consumption for land preparation and sowing for different seeders in wet clay soil with heavy rice residue retention.

Sowing machine	Direct energy (MJ ha^{-1})				Indirect energy (MJ ha^{-1})		Total energy (MJ ha^{-1})
	Residue management	Deep tillage	Compaction	Sowing	Tractor	Other machinery	
DT seeder	1407.8	1801.9	168.9	506.8	225.7	123.2	4234.3
SHT seeder	1407.8	–	–	1013.6	162.0	146.3	2729.7
WR seeder	1407.8	–	–	563.1	54.0	36.6	2061.5

Table 5 – Costs and economic benefit of using different sowing practices in wet clay soil with heavy rice residue retention.

	Sowing machine	Individual item cost (CNY ha^{-1})					Total cost (CNY ha^{-1})	Total income (CNY ha^{-1})	Net income (CNY ha^{-1})	Output/cost
		Seed	Fertiliser	Pesticide	Machinery rental[a]	Labour[b]				
2016/2017	DT seeder	750	1786	900	4650	3600	11,686	21,419	9733 b	1.83 b
	SHT seeder	760	1786	900	3000	3600	10,046	20,287	10,241 a	2.02 a
	WR seeder	780	1786	900	2850	3600	9916	21,425	11,509 a	2.16 a
2017/2018	DT seeder	900	1786	900	4650	3600	11,836	17,614	5778 b	1.49 b
	SHT seeder	825	1786	900	3000	3600	10,111	19,459	9348 a	1.92 a
	WR seeder	825	1786	900	2850	3600	9961	19,528	9567 a	1.96 a
2018/2019	DT seeder	885	1786	900	4650	3600	11,821	14,495	2674 b	1.23 b
	SHT seeder	825	1786	900	3000	3600	10,111	15,647	5536 a	1.55 a
	WR seeder	825	1786	900	2850	3600	9961	14,236	4275 a	1.43 a
Av.	DT seeder	845	1786	900	4650	3600	11,781	17,843	6062	1.51
	SHT seeder	803	1786	900	3000	3600	10,089	18,465	8375	1.83
	WR seeder	810	1786	900	2850	3600	9946	18,396	8450	1.85

[a] Machinery rental was calculated based on local service provider prices, including machinery for rice residue management, soil tillage, sowing, and harvesting.

[b] Three labourers were needed during entire wheat season for spraying, top-dressing, and harvest assistance. Different lowercase letters show significant differences between treatments for the same parameter in the same year using ANOVA *LSD* test ($p < 0.05$).

Table 6 – Effect of rice residue managements on seedling establishment and grain yield of WR seeder in wet clay soil.

Stubble status	Sowing depth (mm)	SER (%)	CV% of seedlings	Grain yield (Mg ha^{-1})
Original	12.0 b	66.3	6.0	7.33 b
Chopped	34.8 a	68.9	2.9	7.92 a
Mulched	38.3 a	66.8	3.8	8.89 a

SER, Seedling emergence rate, CV, coefficient of variation. Different lowercase letters show significant differences between different treatments for the same parameter using the ANOVA *LSD* test ($p < 0.05$).

effective for wheat sowing after the rice harvest in ZT fields with high soil moisture.

4.1. *Effect of WR seeder on wheat grain yield*

This study evaluated the yield advantage of the WR seeder over conventional practices, which was most evident at the farm level (Fig. 6). By improving the sowing and seed covering components, the WR seeders overcame the wet soil conditions for better seedling establishment after paddy rice harvesting, leading to an improved grain yield. The results from both on-station and on-farm experiments indicated that the improved WR seeder yields resulted from the substantial increase in fertile spikes, which may be attributed to the optimal seed placement in the topsoil in lightly disturbed soil. Under the ZT or strip-till conditions, placing seeds in a relatively shallow soil layer facilitated seedling emergence and reduced tillering resistance (Loeppky, Lafond, & Fowler, 1989; Kirby, 1993). Seeding depth should be increased appropriately due to coarse tillage in wet clay fields for better seedling stands as indicated by the farming experiences. However, it is feasible to reduce the sowing depth under the ZT conditions because of its water-conserving effect in wet fields (Ding et al., 2021). Furthermore, reduced or zero tillage soil disturbance, protected soil structure, benefitted wheat growth and development (Bhattacharyya, Kundu, Pandey, Singh, & Gupta, 2008), which confirmed the improved agronomic properties at wheat tillering stage of both the WR and the SHT seeder treatments (Table 2).

The results from the on-station experiment showed a significantly higher yield achieved with the WR seeder compared to the DT seeder only in the second year, while relatively smaller yield gaps were observed between the WR seeder and other types of seeders in the remaining two years. This might be due to controlled conditions of the sowing operations and improved field management for all treatments. In any case, the on-station data confirmed that the WR seeder could produce equivalent or higher yields than the DT seeder due to the improved tillering capacity and productive spike numbers.

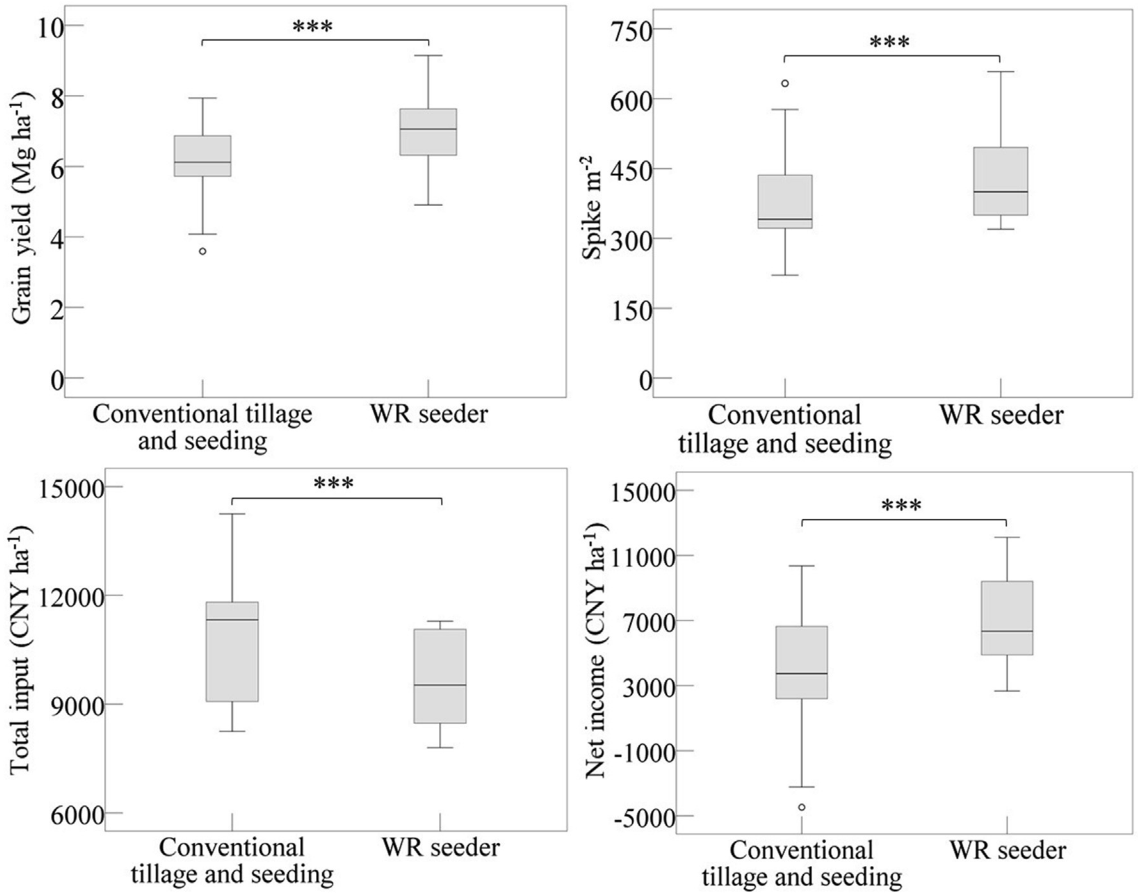

Fig. 6 – Comparisons of WR seeder with conventional tillage and seeding practices in terms of grain yield, spikes per m^2, total cost, and net income in 23 on-farm experiments in 18 locations across the YRB from 2017 to 2020. Boxplots represent the median (black line), 25–75% (box) and the furthest data point within 1.5 times the interquartile range (whiskers), outliers are shown as open circle (n = 23). * indicates statistically significant differences at $p < 0.001$ using paired t test.**

The grain yield performance at a farm level varied considerably depending on the soil texture, moisture, residue retention, and weather conditions. As indicated by Zhang et al. (2020), soil moisture and residue retention are the two key constraints for ZT wheat establishment in the YRB. Our on-station studies indicated that the residue status significantly impacted the WR seeder performance and crop establishment (Table 6). Thus, a flail mower was implemented for residue management to reduce these adverse effects. Furthermore, in India, soil texture had a significant impact on the performance of seven-row Turbo Happy Seeder, and the yield obtained from coarse-textured soil was inferior to that of heavier-textured soil (Sidhu et al., 2015). In the present study, the soil clay content was highly variable (14.3%–44.2%) and had no apparent relationship to either the WR seeder grain yield or yield gaps between the different sowing practices, indicating that the WR seeder was adaptable to varied soil textures.

Although the ZT direct seeding was achievable to the SHT seeder, the spaces between rotary blades and disc openers were easily blocked by residue and wet clods, limiting the applicability to wet clay fields (Fig. A5). In most cases, suitable soil moisture conditions was required to use the SHT seeder.

4.2. *Effect of WR seeder on soil moisture during wheat growth*

One of the reported benefits of ZT combined with maximised soil surface residue retention is the reduction in soil surface evaporation, infiltration, and increased storage of available water in the root zone (Ranaivoson et al., 2017). In the current study, throughout most growth stages, the topsoil moisture content was greater in the WR seeder treatments compared to the DT seeder. Pittelkow et al. (2015) reviewed the variations in crop grain yield under ZT and straw-mulching conditions worldwide using 678 studies and reported that the resultant yield increases occurred in rainfed cropping systems, especially in dryer climates. In the IGP, the evaporation is high, and the ZT practices provide benefits such as increased water use efficiency and reduced irrigation frequency (Erenstein & Laxmi, 2008). The present study confirmed that the WR strip-till seeders in the YRB humid climate also had a favourable effect on soil moisture retention during the entire wheat season, which was beneficial to the plant growth during the middle to late stages of the wheat season receiving less rainfall.

4.3. *WR seeder energy consumption and effects of residue retention*

Reduced operations of the WR seeder saved energy required for wheat production. Compared to the traditional practices, the unit energy consumption was reduced by 51.3% by planting with a six-row WR seeder thanks to the removal of tillage operations and reduced soil disturbance. In addition, crop residue retention as a mulch layer may increase the difficulty of planting and crop establishment (Sidhu et al., 2015; Somasundaram et al., 2020), in the present study, however, by improving residue managements (mulching by a flail mower) and sowing machinery, wheat sowing in wet fields with heavy rice straw retention exhibited clear advantages. According to previous studies (Jat et al., 2014; Singh, Phogat, Dahiya, & Batra, 2014), residue retention can increase soil organic matter content in RW systems. Therefore, wheat production with the WR seeder is a more sustainable way for the RW cultivation.

However, as previously reported (Erenstein, 2003), residue mulching may carry-over pests or inoculum from the previous crop or intensify the plant pest infestation due to better living pest conditions provided by residue. In our investigations, no pests, such as army worms or yellow stem borers, were found to be carried on the mulched residue. On the other hand, all standing stubble and residue would be smashed with a flail mower, which may also kill insect pests. Even so, the impact of residue retention on the occurrence of diseases and insect pests will be concerned in future studies.

4.4. *Future improvements to WR seeder*

More challenges for effective wheat establishment in the RW systems remain. Firstly, the application of high-yielding techniques combined with high-yielding rice hybrids increases the volume of rice straw (residue) retained in the field. Secondly, in very wet and poorly structured soils, tractors often cause deep soil rutting leading to poor plant stands. Consequently, uniform distribution of crushed rice residue is essential. Furthermore, more expensive crawler tractors with increased flotation have recently been tested.

5. Conclusions

The wet clay soil with heavy rice residue retention limits the efficiency and performance of the conventional wheat seeders in the RW system in the YRB. In the present study, we developed and evaluated a series of WR seeders adapted to wet climates, complex soils, and residue retention conditions following rice harvest. The key improvements included strip-tillage to reduce mud/residue blockage, blades with medium bent C type creating a furrow with suitable width and depth for seed placement, two rubber-covered star ground wheels used for controlling the fertiliser and seed metering device, and a stainless-steel chain mounted behind the machine for assisting seed coverage. These improvements significantly enhanced the sowing efficiency and seedling establishment. Over three years of on-station comparison, the WR seeder produced similar or significantly higher grain yields than the DT seeder, and the averaged net income increased by 39.4%. Across 23 on-farm trials, the averaged grain yield increased by 13.9% compared to the conventional practices, and the averaged net income increased by 79.8%. The yield enhancement with the WR seeder was mainly due to the large increase in fertile spikes, and the increase in net income resulted from both the increase in grain yield and the decrease in energy consumption and production costs. Therefore, sowing with the WR seeder is an effective approach to improve grain yield and benefits of wheat in wet clay fields with high reside loads in the RW rotation system.

Author contributions

Chaosu Li and Yonglu Tang conceived and designed the wet-resistant strip-till seeder and the field experiments. A.D. McHugh participated in the improvement of the seeder. Min Liao drew the diagrams of the improved seeder and its blades. Chaosu Li, Xiaoli Wu, Miao Liu, Ming Li and Tao Xiong conducted the field experiments on-station. Dong Ling, Qing Tang, Shizhou Du, Jie Zhu and Yan Huang performed the field investigations of on-farm experiments. Chaosu Li, Xiaoli Wu, Miao Liu, and Ming Li conducted data analysis with supervision from Yonglu Tang and A.D. McHugh. Chaosu Li, Yonglu Tang and A.D. McHugh prepared the manuscript. All authors read and approved the final manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biosystemseng.2022.05.019.

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