

Design and Evaluation of a Machine Integrating Ridge-Breaking, Fertilizing, and Ridging for Ratoon Sugarcane Without Intertillage

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Abstract Existing ratoon sugarcane management machinery cannot satisfy the new agronomic requirements for the integration of ratoon sugarcane ridge-breaking, fertilizing, and re-ridging. Thus, a machine integrating these functions for ratoon sugarcane was designed. The machine structure and key components were designed in accordance with the analysis results of the agronomic requirements. The field orthogonal experiments indicated that the factors affecting the broken rate of soil are speed of rotary shaft, forward speed, and working depth. The influence on the hilling height includes the following aspects: working depth, speed of rotary shaft, and forward speed. Analysis of variance showed that the speed of rotary shaft and forward speed had exceedingly significant effect on the broken rate of soil, the working depth had exceedingly significant effect on the hilling height, and the speed of the rotary shaft reached a significant level. When the tractor was at low gear III and its forward speed was 1.2 m/s, the speed of the rotary shaft was 300 r/min, and the working depth was 20 cm, the verification experiments indicated that the hilling height and the broken rate of soil were 87.4% and 17.0 cm, respectively. The combination of these operating parameters could obtain a better balance

between effect and efficiency. Results of production experiments showed that the field performance of the machine satisfied the agronomic requirements, and the ratoon sugarcane sprouted and grew well in the experimental area. The research provided a supporting machine to promote the application of new agronomic practice for ratoon sugarcane management.

Keywords Machine for field management · Ratoon sugarcane · Ridge-breaking · Integration · Orthogonal experiment

Introduction

Sugarcane is one of the most important sugar crops in China, where sucrose production is approximately 90% of the sugar production (Bai 2021). Sugarcane is planted in an area of approximately 1.08 million hectares in China, of which the ratoon sugarcane accounts for 50% to 70% of the cultivated area (Chen and Hu 2021; Zhou et al. 2013). Quality and yield of ratoon sugarcane are important to sugar industry (Singh et al 2011).

Agricultural scientists have presented a new agronomic practice that integrates ratoon sugarcane ridge-breaking, fertilizing, and re-ridging to enhance productivity and develop simplified cultivation techniques for ratoon sugarcane. This agronomic practice is as follows. First, ridges are broken immediately after sugarcane harvesting, trash shredding, and stubble shaving. Second, the soil is crushed and mixed with shredded trash. Finally, the slow-release fertilizer is earthed up, and the crushed soil is used to cover the stubbles. This new agronomic practice can reduce rot diseases caused by stubble exposure, maintain warmth, prevent frostbite, loosen the soil, and promote the sprouting

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of underground buds. Furthermore, given that the inter-tillage season in the seedling stage is extremely short, and inaccurate time can cause yield reduction (Li 2010; Liu et al 2021), this agronomic practice dispenses with inter-tillage of seedling stage. Therefore, this agronomic practice can increase productivity and reduce cultivation cost.

At present, to reduce ratoon sugarcane management cost, scholars have carried out research on ratoon sugarcane management machine. A small ratoon sugarcane ridge-breaking fertilizer applicator mounted with a walking tractor was developed to solve the operation problem in small hills (Xu et al. 2014). The 2CLF-1 ratoon sugarcane field managing machine was designed for conventional operations, such as stubble shaving, ridge-breaking, fertilization, and film mulching (Qin et al. 2015). Tang et al. (2019) developed a machine for ratoon sugarcane shoveling. Singh et al. (2017a) designed and developed a disk-type sugarcane ratoon management device for ratoon field with trash and evaluated in sandy loam soil. Choudhary et al. (2017) modified and upgraded a machine into multipurpose SORF machine, and its performance was evaluated with field experiments and contrasted with conventional practice. This research was aimed at conventional agronomic operations, given that studies on the supporting machine for the new agronomic practice are limited. The existing machinery was inapplicable to new agronomic requirements. Thus, a machine integrating ridge-breaking, fertilizing, and ridging for ratoon sugarcane was designed. The machine was evaluated in a series of field experiments.

Materials and Methods

An integrated machine was designed and developed in accordance with new agronomic requirements. It consisted of base frame, plow of ridge-breaking, transmission, rotary tillage unit, fertilizer unit, hilling unit, and ridge compacting unit (Fig. 1). The working units could be adjusted in accordance with different row spacing. The working processes of the machine are shown in Fig. 2, and the technical parameters are shown in Table 1.

Transmission Unit

The working power of the entire machine was provided by a tractor and delivered through a transmission unit. It consists of a transmission shaft, worm drive box, bevel gearbox, hexagonal shaft, and a series of driving chains (Fig. 3). Initially, the power take-off (PTO) driveshaft transmitted power to the bevel gearbox by transmission shaft. Then, the gearbox transmitted power to the chain drive unit and fertilization gear on both sides. Finally, the

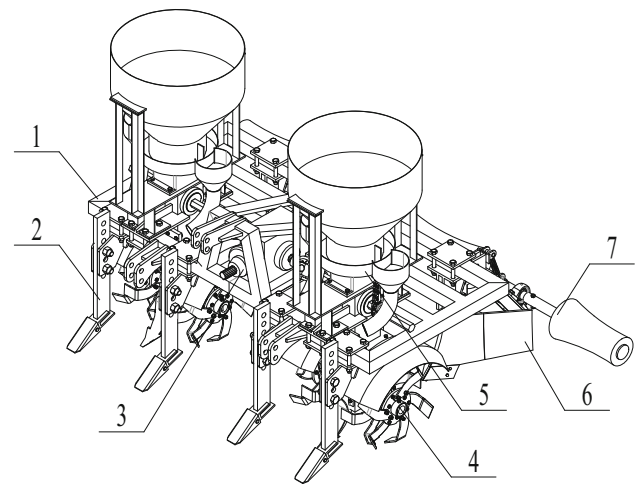


Fig. 1 Schematic of the integrated machine. 1 base frame, 2 plow of ridge-breaking, 3 transmission unit, 4 rotary tillage unit, 5 fertilizer unit, 6 hilling unit, and 7 ridge compacting unit

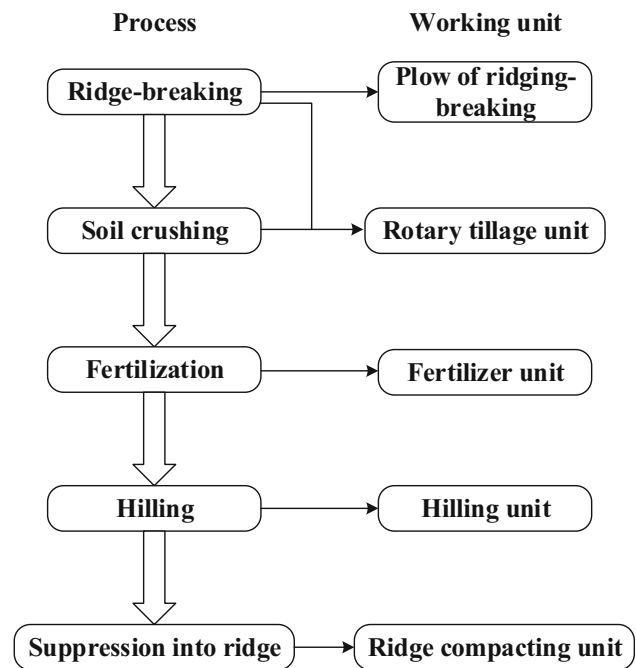


Fig. 2 Schematic of the working process

rotary blade unit was driven by the chain drive unit to rotate, the fertilization gear transmitted power to the worm gear by chain drive, and the fertilizer turntable was driven by the worm drive to rotate.

Base Frame

Base frame was designed to rigidly support different components, and it was provided with three-point linkage for connecting with the tractor. It was made of mild steel square pipe (80 mm × 80 mm) with a wall thickness of

Table 1 Technical specification of the integrated machine

S. no	Particular (s)	Details
Complete machine		
1	Matched power of tractor (kW)	88.2
2	Overall weight (kg)	1159
3	Width of the integrated machine (mm)	3020
4	Length of the integrated machine (mm)	2075
5	Height of the integrated machine (mm)	1979
6	Number of working row	2
7	Row spacing (mm)	1200–1400
Operating parameter		
1	Forward speed (m/s)	0.6–1.2
2	Maximum working depth (mm)	200
3	Rotational speed of rotary tillage unit (rpm)	200–300
Transmission unit		
1	Bevel gearbox speed ratio	1.8:1
2	Chain drive unit speed ratio	1:1
3	Chain drive of fertilization speed ratio	1.2:1
4	Worm drive box speed ratio	20:1
Base frame		
1	Material	Mild steel square pipe 80 mm × 80 mm × 8 mm
2	Length (mm)	1350
3	Width (mm)	2220
4	Height (mm)	600
Plow of ridge-breaking		
1	Material of plow body	30-mm-thick medium steel
2	adjustable range (mm)	240
3	Number of the plow	4
Rotary tillage unit		
1	Width of the rotary tillage (mm)	700
2	Radius of rotary tillage (mm)	265
3	Blade	8-mm steel spring plate with bended body and sharpened edges
Hilling unit		
1	Material of plow standard	30-mm-thick mild steel plate
2	Material of mold board	5-mm-thick high manganese steel plate
3	width (mm)	400–700
4	height (mm)	370
Ridge compacting unit		
1	Material of roller	roller body
2	Width (mm)	3000
3	Compacting strength (kPa)	40–60
Fertilizer unit		
1	Material of fertilizer box	1-mm stainless steel
2	Capacity of a fertilizer box (m ³)	0.25
3	Distributing type	Feed unit of guide plate and turn table
4	Each side distributing ability (kg/ha)	400–1200

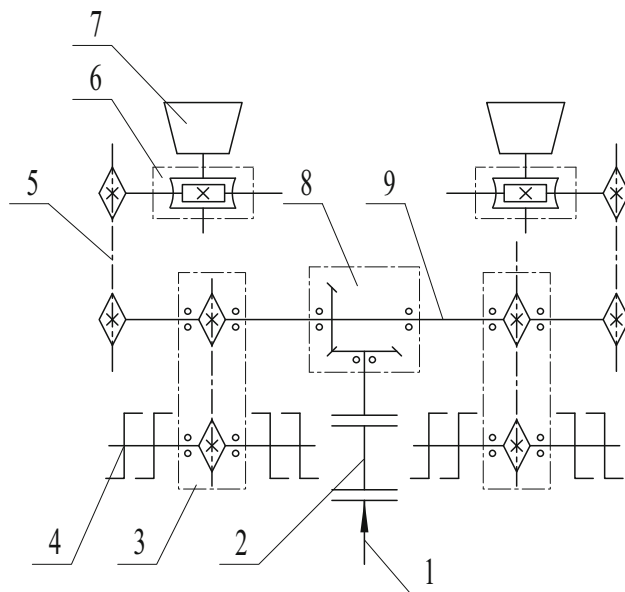


Fig. 3 Power transmit diagram of the transmission. 1 PTO shaft, 2 transmission shaft, 3 chain drive unit, 4 rotary blade unit, 5 chain drive of fertilization, 6 worm drive box, 7 fertilizer unit, 8 bevel gearbox, and 9 hexagonal shaft

8 mm. The power of the machine was provided by the tractor, which was connected through the three-point linkage of the frame to pull the machine forward and control the cutting depth.

Plow of Ridge-Breaking

The front of the frame was designed with four plows of ridge-breaking to split and pre-loose the solid soil in the area to be rotated to reduce the working resistance of the rotary tillage unit and improve soil crushing rate and reliability of the rotary tillage unit. In addition, the plow was used for cracking the soil near the root to increase the permeability and cutting of side old roots. Each plow consisted of a mounting base and plow body with holes at 60-mm intervals for depth adjustment, as required (Akhalaya and Shogenov 2017; Salar et al. 2013). Replaceable high manganese steel colter was mounted on the plow body by pin to protect plowshare from being worn. The selected penetrating angle was 27° , and the gap angle was 10° (Fig. 4).

Rotary Tillage Unit

Rotary tillage unit was designed to spin through the power take-off driveshaft of the tractor at a rotational speed of 200–300 r/min to break the ridge and crush the soil according to the calculation theory and the reference (Zhong et al. 2021). It consisted of a chain drive unit, rotary blade unit, balk plow, and arc-shaped baffle (Fig. 5).

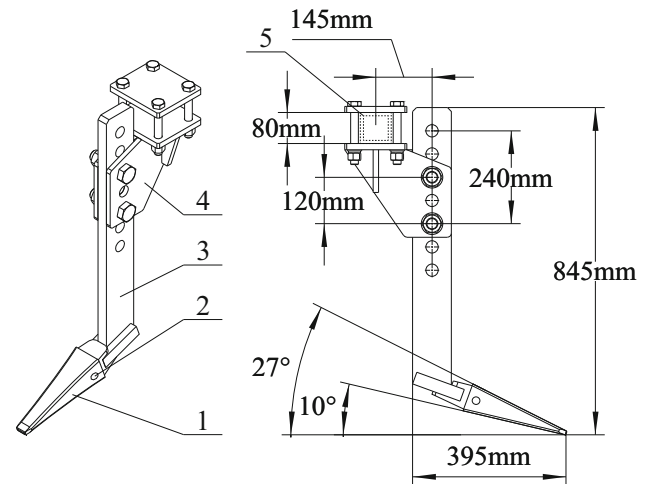


Fig. 4 Design of the ridge-breaking plow. 1 colter, 2 pin, 3 plow body, 4 mounting base, and 5 base frame

The rotary blade unit was connected to the chain drive unit by spline joint. According to tilling width, 12 rotary blades were mounted on two disks of the rotary blade unit, and the cutting area is divided into four parts. The disks were made of 15-mm-thick and 220-mm-diameter circular steel plate, and the drive shaft was made of 80-mm-diameter, 16-mm-thick, and 210-mm-long steel hollow shaft. The working diameter of the rotary tillage was 530 mm, and the designed maximum working depth was 210 mm. The axial thrust effect of the rotary tillage was highlighted, evenly stressed, and worked stably to increase the soil lateral supply; the rotary blades of each rotary blade unit were arranged in a staggered six-head short spiral line (Zhang et al. 2019; Jia et al. 2011). An arc-shaped baffle mounted on top of the rotary blade unit was designed to divert the soil particles thrown by the rotary tillage cutting to the side. The baffle could facilitate subsequent soil accumulation and ridge formation and prevent soil particles from hitting the operators and entering the transmission unit.

Hilling Unit

The hilling plow was mounted on the rear of the frame by mounting base and using fasteners. Each plow consisted of the plow body, two active moldboards, and adjusting mechanism. Replaceable wearing plates were mounted on the plowshare by pin to protect the plowshare from being worn (Fig. 6). The selected materials included 30-mm-thick mild steel plate for plow standard and 5-mm-thick high manganese steel plate for active moldboard. In accordance with the row spacing, the width range of the plow was 400–700 mm with an adjusting mechanism, and the height was 370 mm (Singh et al. 2017b). The plow bottom surface was designed with horizontal straight-line

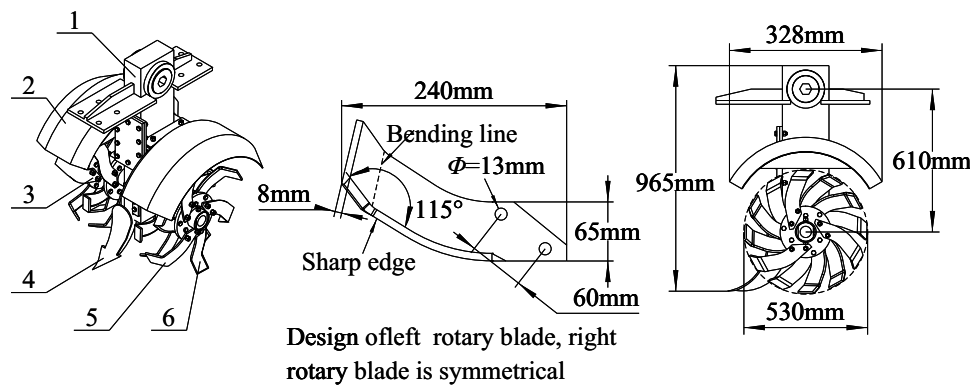


Fig. 5 Design of the rotary tillage unit. 1 chain drive unit, 2 arc-shaped baffle, 3 rotary blade unit, 4 balk plow, 5 right rotary blades, and 6 left rotary blades

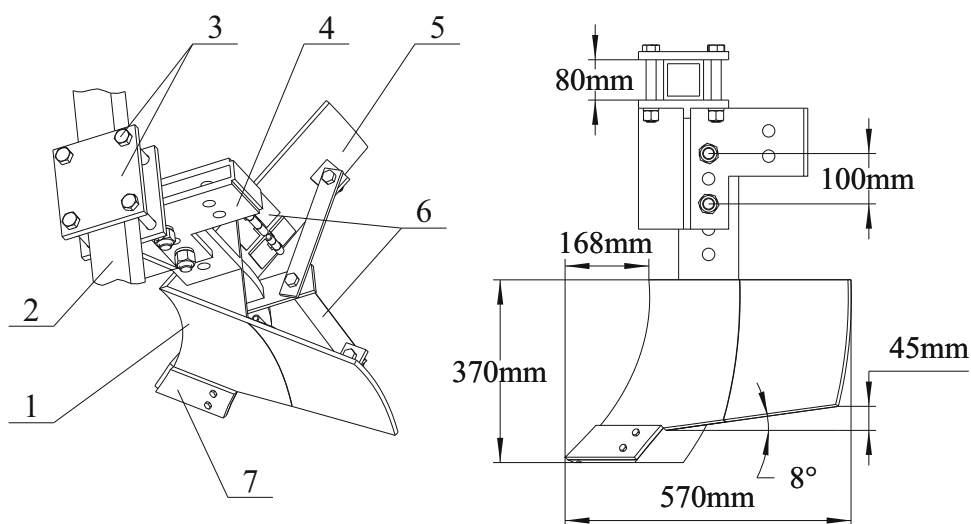


Fig. 6 Design of the hilling device. 1 plow body, 2 square tube of frame, 3 fasteners, 4 mounting base, 5 active moldboard, 6 adjusting mechanism, and 7 wearing plates

elements, the opening of the guiding curve was 232 mm, and the element angle was in the range of 36.5°–40°. The plow squeezed the crushed soil to both sides and covered the stubbles in advance. Then, the soil forms a natural ridge shape for easy compaction according to the repose angle.

Ridge Compacting Unit

Lack of soil in the stubbles can cause accumbent sugarcane, yield reduction of high cutting by sugarcane harvesters, and aboveground buds sprouting. Thus, a ridge compacting unit was designed. When the hilling process was completed, the sugarcane ridge should be reshaped and compacted to form a drum-type ridge shape with single-peak. This shape is beneficial to rainwater flow and avoids lack of soil in stubbles with rain erosion. The unit was

designed as an elastic floating with profiling adjustment to adapt to the change in the sugarcane field. It consisted of regulation spring, connector, and ridge roller (Fig. 7). The traction to the ridge compacting unit was provided through connecting the connector and mounting base of the hilling plow. The ridge roller reshaped and compacted the ridge due to its own weight. When it encountered a large volume of mud that cannot be crushed, the traction resistance of the roller increased, and the spring contraction drove the roller body to bounce up to avoid clogging of the large clod and trash. The large clod and trash in front of the roller increased the traction resistance and affected the forming effect. The minimum diameter of the roller body was 85 mm, and the maximum diameter was 125 mm; the diameter of the mounting shaft was 50 mm, the width of the middle roller body was 700 mm, and the width of the

Fig. 7 Design of the ridge compacting unit. 1 regulation spring, 2 connector, 3 side ridge roller, 4 mounting shaft, 5 middle ridge roller, 6 bearing with housing, and 7 mounting base of hilling plow

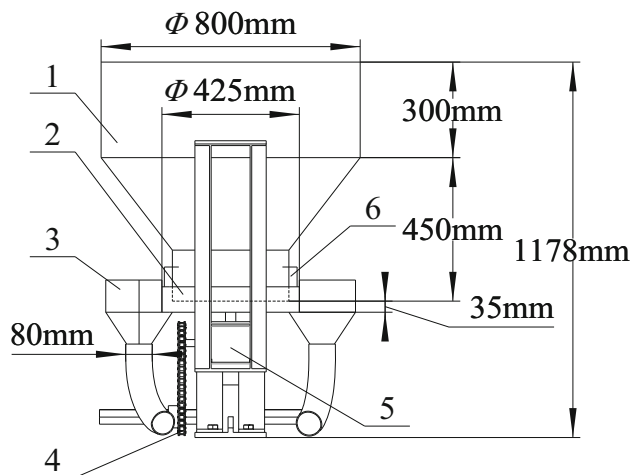
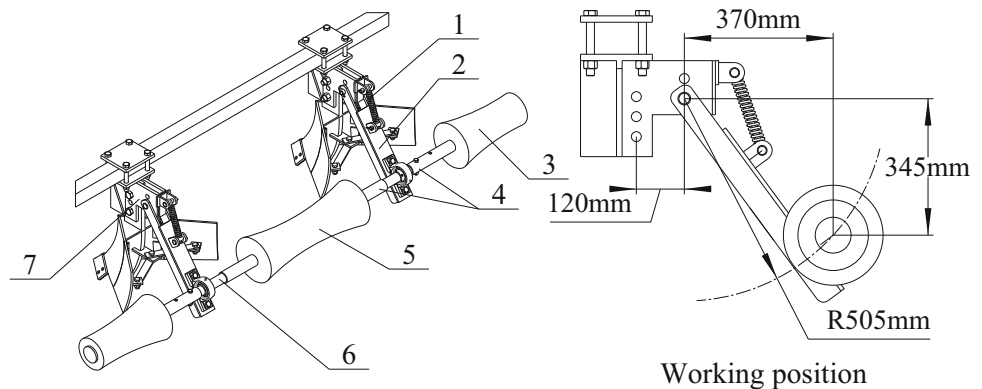


Fig. 8 Design of the fertilizer unit. 1 fertilizer box, 2 turntable, 3 fertilizer pipe, 4 chain drive of fertilization, 5 worm drive box, and 6 guide plates

side roller body was 450 mm. Nylon material was selected for the roller body, and steel hollow pipe was selected for the mounting shaft to reduce the weight of the unit and soil adhesion.

Fertilizer Unit

The slow-release fertilizer of the new agronomic practice was granulated fertilizer. A guide plate fertilizer feed unit was designed to prevent the fertilizer from clogging due to moisture (Fig. 8). Granulated fertilizers spilled from the fertilizer box to the turntable due to their own weight. The turntable served as the feeding conveyor, and the fertilizers flowed from the gap between the fertilizer box and outer turntable through rotation. Then, the fertilizers rose along the slope of the guide plate by thrust to the turntable edge and dropped into the fertilizer pipe to be discharged. Adjusting the guide plate height and gap of the fertilizer box and turntable could control fertilization.

Performance Evaluation

The performance of the integrated machine was evaluated by the operating parameters of the field experiment. The experiment was carried out at the base of research and breeding for sugarcane in the subtropical agricultural science new city of Guangxi, China. The area is located at 22°30'N, 107°46'E with subtropical monsoon climate, having humid hot summer and dry cold winter. The soil in the experimental area was laterite soil in texture (44% clay, 37% silt, and 19% sand). The detailed conditions of the experimental area are shown in Table 2. The experiment was conducted in December 2020 (Fig. 9).

Experimental Factors and Indicators

The effects of the operating parameters on the agronomic indicators were investigated in the experiments. The parameters included forward speed of the machine, speed of the rotary shaft, and working depth in accordance with the actual operating conditions of the tractor driver. The indicators included the broken rate of soil and hilling height in accordance with the agronomic requirements.

Flat and stable working areas were selected as the measurement areas, and the measurement point was obtained every two meters along the row, with a total of 10 points. The height of the soil ridge formed by burying the stubbles was measured, and the schematic of the measurement is shown in Fig. 10 (Zhang et al. 2018). In addition, the mean value of the hilling height was considered for this measurement. DHF-LX1204 tractor was used for power.

In the same measurement area, one measurement point was obtained every three meters, with a total of three points. An area of 0.5 m in length along the row and width of soil disturbance range was selected in each measurement point. Soil blocks of the area were divided into two parts in accordance with the maximum diameter, as follows: the unbroken soil blocks with a maximum diameter greater

Table 2 Soil condition of the experimental area

Ratoon field condition		Soil condition		
Ratoon field type	Mechanical harvesting	Depth (cm)	Soil moisture (%)	Soil hardness (N/cm ²)
Above sea level (m)	96.24	0–5	7.26	147
Sugarcane varieties	Zhongzhe 9	5–10	9.88	311
Row spacing (m)	1.4	10–15	11.8	535
Soil type	laterite	15–20	14.34	628



Fig. 9 Field experimental of operating parameters



Fig. 10 Field measurement of the hilling height

than 25 mm and the broken soil blocks with maximum diameter below 25 mm (Lv et al. 2019). The two parts of the soil blocks were weighed separately. The broken rate of soil was calculated according to Eq. (1), and its mean value was considered for this measurement.

$$S_t = \frac{W_s}{W_s + W_w} \times 100\% \tag{1}$$

where S_t is the broken rate of soil, %, W_s is the weight of broken soil blocks, kg, and W_w is the weight of unbroken soil blocks, kg.

Field Experiment Design

A three-factor three-level orthogonal experiment was designed to study the effect of forward speed of the machine, speed of the rotary shaft, and working depth on the indicators, as well as the optimal combination of these operating parameters. The levels were preliminarily confirmed by theoretical calculation and design requirements prior to the experiment. I low, II low, and III low operating gears were selected as the levels to characterize the forward speed of the machine according to the technical parameters of the tractor and machine technical specification because the forward speed of the machine was determined by the tractor gear. The speed range is 0.65–1.2 m/s (Xiao 1999). The coding table of the experiment factors and levels is shown in Table 3. Orthogonal table was selected as the experimental arrangement, and nine sets of experiments were performed. The experimental arrangement and mean values of the results are shown in Table 4.

Results and Discussion

The variance of the three-factor three-level experimental data was analyzed by Minitab software to investigate the significance of the effect of the factors on the indicators. The significance test was performed with p value, and the result is shown in Table 5.

According to the analysis of variance, for the broken rate of soil, the parameters in the order of significance were speed of rotary shaft, forward speed of the machine, and working depth. The speed of the rotary shaft and forward speed of the machine had an extremely significant effect on the broken rate of soil with p value; the effect of the working depth was insignificant. This result was consistent with the theory of the effect of bite length on the quality of broken soil, where the forward speed was higher, the bite

Table 3 Experimental factors and levels

Levels	Experimental factors		
	Forward speed of the machine A	Speed of the rotary shaft B (rpm)	Working depth C (cm)
1	I low	200	100
2	II low	250	150
3	III low	300	200

Table 4 Design scheme and results of the orthogonal experiment

S. no	Forward speed A	Speed of the rotary B (rpm)	Working depth C (cm)	Broken rate of the soil S_t (%)	Hilling height H_R (cm)
1	1 (I low)	1 (200)	1 (10)	83.9	7.9
2	1	2 (250)	2 (15)	88.9	13.4
3	1	3 (300)	3 (20)	92.4	17.6
4	2 (II low)	1	2	80.9	12.2
5	2	2	3	87.4	17.6
6	2	3	1	90.1	9.4
7	3 (III low)	1	3	79.1	17.2
8	3	2	1	84.0	8.7
9	3	3	2	87.3	14.2

Table 5 Variance analysis results of the orthogonal experiment

Experimental indicators	Source	Sum of squares	DF	Mean square	F value	P value	Sig
Broken rate of soil S_t (%)	A	36.58	2	18.29	130.64	0.008	**
	B	114.44	2	57.22	408.71	0.002	**
	C	0.54	2	0.27	1.93	0.341	
	Error	0.28	2	0.14			
	Total	151.84	8				
Hilling height H_R (cm)	B	2.58	2	1.29	7.59	0.04	*
	C	116.24	2	58.12	341.88	< 0.001	**
	Error	0.68	4	0.17			
	Total	119.50	8				

*Significant at 5% (level of significance), p value < 0.05—significant at 5%, ** p value < 0.01—extremely significant at 1%

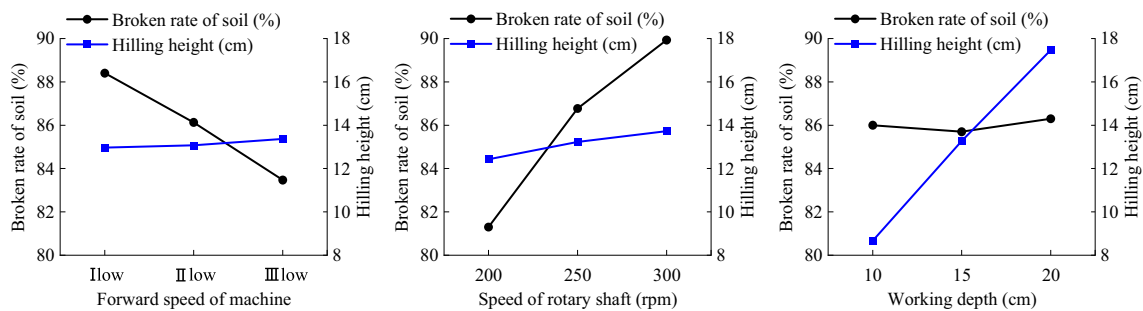


Fig. 11 Main effect plot for the broken rate of soil and hilling height

length was longer, and the broken rate of soil was lower. The higher speed of the rotary shaft indicates smaller bite length and higher broken rate of soil. Under the condition of uniform soil quality in the field, the working depth unaffected the bite length; thus, the effect on the broken soil rate was insignificant.

For the hilling height, because the mean square of factor A was smaller than the mean square of the error, the forward speed of the machine slightly affected the hilling height and could be classified as an error (Ren 2009). According to the analysis result, the working depth had an extremely significant effect on the hilling height, and the speed of the rotary shaft had a significant effect. The working depth was extremely significant and indicated that the larger working depth results in greater excavation amount and higher hilling height. The speed of the rotary shaft was significant and indicated that the higher speed leads to more soil thrown out, thereby effectively increasing the hilling height.

The main effect plots are shown in Fig. 11; the mean level of two indicators had three factors, and the range analysis was performed (Table 6). Figure 11 and Table 6 show that the primary and secondary factors influence the broken rate of soil; they include speed of the rotary shaft, forward speed of the machine, and working depth. The optimal combination of the operating parameters, namely $B_3A_1C_3$ positively affected the broken rate of soil. The working depth had the greatest effect on the hilling height, followed by the speed of rotary shaft; the forward speed of machine had the least effect. The optimal combination was $C_3B_3A_3$. The result was consistent with the analysis of variance.

Verification Experiment

According to the range analysis, the optimal combination for two indicators was different. The optimal level of factors that significantly affected each indicator was selected, and the optimal combination $A_1B_3C_3$ of the two indicators was obtained from the results of the orthogonal experiment. However, the combination $C_3B_3A_3$ with the greatest hilling height was not obtained from the orthogonal experiments. Furthermore, the actual working process not only considered the effect but also the efficiency. According to the basic requirements of agricultural mechanization for the construction of high-quality and high-yield sugar cane base in Guangxi, the broken rate of soil reached 85%, and the hilling height reached 15 cm with the agronomic requirements.

According to Table 4, the combinations that satisfied the agronomic requirements were $A_1B_3C_3$ and $A_2B_2C_3$. However, the optimal combination $A_3B_3C_3$ for the hilling height was not obtained from the orthogonal experiments. Therefore, a ratoon field with slope and soil conditions similar to the experimental area was selected to carry out verification experiments. The result is shown in Table 7.

Three parameter combinations satisfied the agronomic requirements based on the verification result of the experiment. The field efficiency was determined by the forward speed of the machine. Thus, to avoid missing the farming season and to reduce the cost of operation, the $A_3B_3C_3$ combination with higher efficiency could be selected when the best effect was not required.

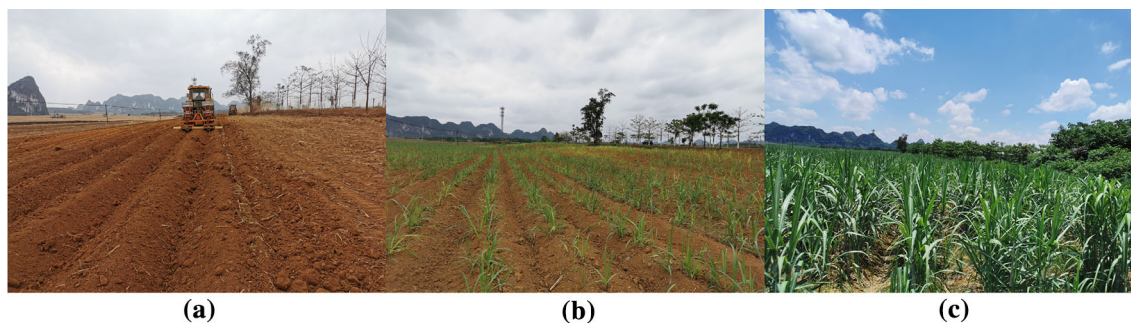
After the test prototype was adjusted and improved, the production experiment was carried out at the base in the crushing season for 2020–2021. The production experiment status is shown in Fig. 12.

Table 6 Range analysis results of orthogonal experiment

Experimental indicators	Items	Forward speed of machine A	Speed of rotary shaft B	Working depth C
Broken rate of soil S_i (%)	k_1	88.40	81.30	86.00
	k_2	86.13	86.77	85.70
	k_3	83.47	89.93	86.30
	R	4.93	8.63	0.60
	Priority	B > A > C		
	Optimum	$B_3A_1C_3$		
Hilling height H_R (cm)	k_1	12.97	12.43	8.67
	k_2	13.07	13.23	13.27
	k_3	13.37	13.73	17.47
	R	0.40	1.30	8.80
	Priority	C > B > A		
	Optimum	$C_3B_3A_3$		

Table 7 Results of verification experiment

Combinations	Broken rate of soil (%)	Hilling height (cm)
A ₂ B ₂ C ₃	86.4	16.5
A ₁ B ₃ C ₃	91.2	16.8
A ₃ B ₃ C ₃	87.4	17.0
agronomic requirements	≥ 85	≥ 15

**Fig. 12** Production experiment status. **a** Experimental site, **b** seedling status of 50 days, and **c** seedling status of 130 days

Economic Analysis

For example, in the Guangxi sugarcane area of China, the conventional ratoon management included ridge-breaking and intertillage of seedling stage. The total cost of machine operation included the abovementioned components; the average was between ¥1200 and ¥1500 per ha. However, the cost of integration included ratoon ridge-breaking, fertilizing, and re-ridging without intertillage of the seedling stage. The cost was between ¥900 and ¥1050 per ha and reduced by ¥300–450 per ha compared with the conventional practice (1 Chinese Yuan = 0.16 US\$).

Conclusions

A machine integrating ridge-breaking, fertilizing, and ridging for ratoon sugarcane was designed in accordance with the new agronomic requirements. A series of field and production experiments were conducted for the test prototype. The field performance and seedling status showed that the integrated machine can satisfy the agronomic requirement. This study introduced an agricultural machine for popularization and application of the new agronomic practice.

The influence law of each operating parameter on the effect was obtained through the orthogonal experiment. The speed of the rotary shaft and the forward speed of the machine had an extremely significant effect on the broken rate of soil. The working depth had an extremely

significant effect on the hilling height, and the speed of the rotary shaft had a significant effect.

Three parameter combinations that satisfy the agronomic requirements were obtained through verification experiment in the field and provided basis for selecting operating parameters for operators in field practice. The combination of operating parameters that could consider the effect and efficiency was III low for forward speed, speed of the rotary shaft at 300 rpm, and working depth of 20 cm. The broken rate of the soil for this combination was 87.4%, and the hilling height was 17.0 cm.

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Authors' Contributions Shang-Ping Li, Jia-Feng Pan, Jia-Qin Zhong, Wei Li, De-Quan Yang, and Qing-Gui Mo performed analysis on all samples, interpreted data and wrote the manuscript. All the authors read and approved the final manuscript.

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Declarations

Conflict of Interest The authors declare that they have no conflict of interest.

Human and Animal Rights This article does not contain any studies with human participants or animals performed by any of the authors.

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