Sugar Tech (Sept-Oct 2021) 23(5):1147–1156
https://doi.org/10.1007/s12355-020-00927-7

RESEARCH ARTICLE

Design and Evaluation of a Novel Transversal Double-bud Sugarcane Planter with Seed Pre-cutting

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Received: 11 August 2020 / Accepted: 16 November 2020 / Published online: 28 March 2021

Abstract Transversal double-bud sugarcane planting with seed pre-cutting is an advanced method with great development prospect. This technique ensures a high bud ratio, strong tillering capability and reduced seed consumption. Moreover, it obtains a long ratoon period, a high yield and Pol property. The transversal sugarcane planter must satisfy the agronomic requirements of precise planting with deep furrowing, orderly and uniform transversal seeding and consistent fertilization. Here, a novel transversal double-bud sugarcane planter was designed with the following main components: furrow openers, seeding units, fertilizers, seed compensators and soil cover units. The effects of rotary tillage speed, sprocket speed, chain inclination, seed cane box inclination, forward speed and cam's speed and repose angle were studied in the laboratory to determine the best structure and working parameters of the units. Furrowing, seeding and fertilization performances were evaluated in a field test. Experimental results showed that the furrow depth stability was above 89% at 540 r/min output speed of the tractor. The seeding depth of 20.8–21.8 cm was less than the furrowing depth of 30 cm. The qualified rate of seeding was 91%, and the seeding interval was within the range of 330–495 mm. The fertilization interval was stable at 113.5–117.1 mm when cam's repose angle was 38°, and the forward speed was I–III low gear. This planter only required approximately 4.4 t/ha seed canes, which was 51–75% lower than that for the traditional method. Its performance parameters indicated acceptable results.

Keywords Transversal double-bud sugarcane planter · Furrow · Seeding · Fertilization

Introduction

Transversal sugarcane planting with seed pre-cutting is a new mode to develop advanced sugarcane varieties. Single-, double- and multi-bud seed canes are commonly used in pre-cutting sugarcane segments. Transversal double-bud sugarcane planting with seed pre-cutting has the following advantages: double-bud sugarcanes have a high budding rate, low seed consumption (approximately 1/2–1/3 of traditional vertical planting) and strong tillers. Single buds have a high rot rate and poor field survival rate (Clements. 1940; Jain et al. 2010). Double-bud canes yield more than single- and multiple-bud canes (Yadav et al. 2013; Chitkala et al. 2011; Luo et al. 2019). The planting method is the most important factor affecting parameters (Kumar et al. 2019). Transversal planting has stronger lodging resistance and tillering capability than vertical planting and increases the yield of cane stem by 6.61% (Yang et al. 2015). Transversal double-bud sugarcane planting pattern has many advantages and broad application prospects but currently only relies on artificial planting. This method is labor intensive and often difficult to maintain with

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changing seasons (Saengprachatanarug et al. 2018). Therefore, a new type of planter must be developed to meet the requirements of mechanized planting.

The three current mature types of sugarcane planting machines are whole-stalk, real-time cutting and pre-cutting sugarcane planters. Sugarcane planting involves furrowing, seeding, fertilizing and covering; this method requires a deep furrow opener to form a dynamic space to ensure seeding depth and promote sugarcane growth (Singh et al. 2017). The furrowing depth of the transversal double-bud sugarcane planter is twice as deep as that of a traditional planter. The seeding unit should conform to the uniformity and continuity requirements of precise planting. Many scholars focused on the relationship among the position of the chain groove, the speed of the lifting chain angle, the seeding speed, the arrangement method and the precision of seeding (Taghinezhad et al. 2014; Thienyaem et al. 2014; Saengprachatanarug et al. 2018). Limited scientific references are available for the double-bud transversal planter because the mechanization of sugarcane plantation is still in the developmental stage (Ripoli et al. 2010).

In March 2020, the General Office of Guangxi People's Government of China issued the "Guangxi Sugarcane Advanced Variety and Technology Promotion Work Implementation Plan" and proposed that a cumulative combined planting area of 1.05 million Mu must be completed by 2022/2023. Therefore, a planter is urgently needed to meet the agronomic requirements of transversal double-bud sugarcane planting in subtropical hilly areas. In this study, a transversal sugarcane planter was proposed for the sugarcane base in Guangxi, China. Seed pre-cutting and transversal seeding were adopted. Planter performance was evaluated in the laboratory and field.

Materials and Methods

Design of a Transversal Double-bud Sugarcane Planter

The transversal double-bud sugarcane planter was mainly composed of furrow openers, seeding units, fertilizers, seed compensators and soil cover units (Fig. 1). The working process of the planter is shown in Fig. 2, and its technical index parameters are shown in Table 1.

Furrow Opener

Furrowing is the first step in planting and consists of the upper and lower arms, the hydraulic system, rotary tillers, front ploughs, rear ploughs and fenders (Fig. 3). The row spacing between two openers was adjusted to 1400 mm. The furrow depth and cutting angle of the opener can be modified by controlling the upper and lower arm cylinders. The opener can form a trapezoidal deep trench with an adjustable design depth up to 40 cm.

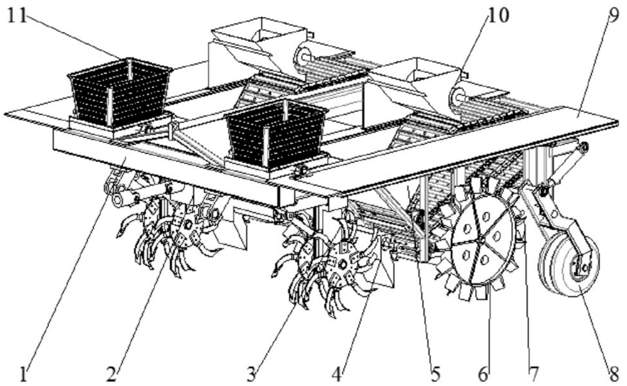

Fig. 1 Schematic view of the transversal sugarcane planter. *1* frame, *2* gearbox, *3* furrow opener, *4* fertilizer, *5* seeding unit, *6* earth wheel, *7* soil cover, *8* depth adjustment auxiliary wheels, *9* cane box activity platform, *10* seed compensator, *11* cane box

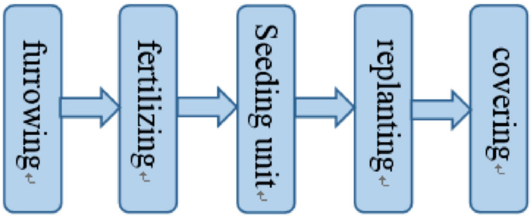

Fig. 2 Schematic diagram of working

Seeding Unit

Sugarcane trough was designed according to the diameter and degree of curvature of canes. The side view of the sugarcane collecting box was designed as an inverted triangle that could accommodate approximately 180 canes. The transmission system of the seed metering device was mainly composed of a primary lifting conveyor chain and a secondary reversing conveyor chain. The chain seed metering device was filled by squeezing seeds into the cane trough with the help of their own gravity (Liu et al. 2016). Seeds move upward with the rotation of the primary conveyor chain, then fall into the secondary conveyor chain, move downward with the rotation of the secondary conveyor chain and then finally fall into the trench opened by the furrow opener. The seeding unit is shown in Fig. 4.

Fertilizer Unit

An intermittent fertilizer unit (Fig. 5) was designed to reduce the cost of fertilization, maintain the fertility of the soil, prevent the burning of seedlings and improve the efficiency and uniformity of fertilization. The rotation of

Table 1 Specification of a novel transversal double-bud sugarcane planter

General		–
1	Source of power (kw)	130
2	Overall weight (kg)	3000
3	Width of the planter (mm)	2100
4	Length of the planter (mm)	3000
5	Height of the planter (mm)	1250
6	Number of row	2
7	Row–row distance (mm)	1400
8	Seeding method	Transversal seeding
Furrow opener	–	–
1	Furrowing form	Combination type with front and rear plough and rotary tillage
2	Transfer method	Chain drive
3	Number of the opener	2
4	Radius of rotary tillage (mm)	300
5	Width of rear plough (mm)	480
Seeding unit	–	–
1	Number of unit	2
2	Transfer method	Chain drive
3	Length of cane trough (mm)	350
4	Top width of cane trough (mm)	47
5	Below width of cane trough (mm)	30
6	Height of cane trough (mm)	24
7	Shape of collecting box	Inverted triangle
8	Capacity of collecting box	180 sugarcanes
Fertilizer unit	–	–
1	Metering method	Composed of screw fertilizer device and cam intermittent mechanism
2	Length of fertilizer mouth (mm)	250
3	Height of screw outlet (mm)	6.8
4	Pitch (mm)	60
5	Fertilized weight (kg/ha)	600–900
6	Fertilization interval (mm)	100–130
Seed compensator	Photoelectric detection	–
Soil cover	Hydraulic control disc for covering with the stroke of 100 mm	–

the screw rod was used to transport the fertilizer in the fertilizer box to the mouth. The door was opened by the rotation of the camshaft to achieve intermittent fertilization. Fertilization quantity was controlled by the size of the screw outlet and the rotation speed of the screw. Fertilization interval was regulated by the speed and structural parameters of the camshaft.

Seed Compensator

A seed compensator (Fig. 4) was installed on the frame. When the missing seed signal was detected, the motor was turned on, and the seed in the compensator box was dropped into the cane trough. When a seed gets lost in the chain trough of the seeding unit, the seed compensator can reseed in time to ensure the seeding qualification rate.

Soil Cover

A double disc was used to cover the soil, and the height of soil covering was adjusted by a hydraulic cylinder. Seed canes were shallowly buried at 5–10 cm depth to facilitate the emergence rate.

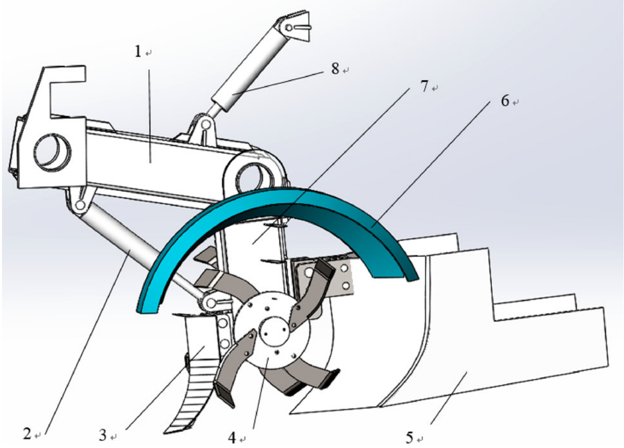

Fig. 3 Structure of the furrow opener. *1* the upper arm, *2* lower hydraulic cylinder, *3* front plough, *4* rotary tillage unit, *5* rear plough, *6* fender, *7* the lower arm, *8* upper hydraulic cylinder

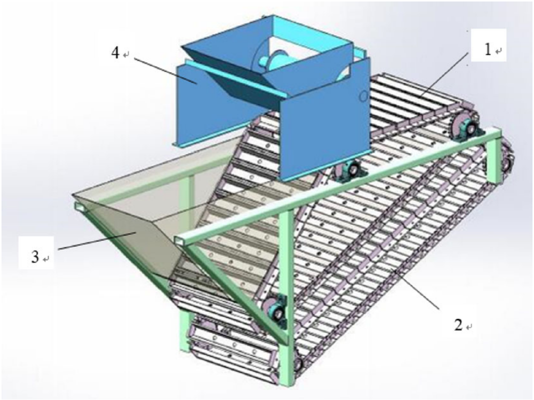

Fig. 4 Structure of the seeding unit. *1* primary lifting conveyor chain, *2* secondary reversing conveyor chain, *3* sugarcane collecting box, *4* seed compensator

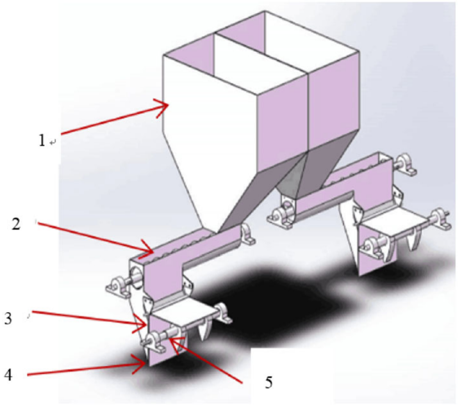

Fig. 5 Structure of the fertilizer unit. *1* fertilizer box, *2* screw rod, *3* fertilizer door, *4* fertilizer mouth, *5* camshaft

Laboratory Evaluation of the Transversal Double-bud Sugarcane Planter

The laboratory evaluation of the planter covered the following:

(1) Laboratory evaluation of the furrow opener. Five levels of rotation speed were driven by an electrical motor to test the voltage and current under no-load conditions to calculate the rotating tillage power.
(2) Laboratory evaluation of the transversal seeding to determine operation parameters for seeding. Five levels of sprocket speeds, chain inclinations and sugarcane box inclination were used to analyze the seeding qualification rate.
(3) Laboratory evaluation of the fertilizer unit. Five levels of forward speed, camshaft speed and camshaft repose angle were used to evaluate the fertilizer unit.

Field Operation of the Transversal Double-bud Sugarcane Planter

The field performance test of the planter was tested to determine the most effective, feasible and sustainable planting technique for transversal sugarcane cultivation in the field. This evaluation was conducted in the advanced sugarcane varieties research and development and breeding base of Guangxi Sugar Industry Cooperative Centre (located at 107.8°E, 22.4°N, China) in 2019–2020 (Fig. 6). The soil of the field was red clay with moisture content, firmness and density of 20%, 185.5 N/cm^2 and 1.935 g/cm^3, respectively. The test field was relatively flat and contiguous, and the slope of the planting plot was not more than 5°. LOVOL M1854-G tractor was used for power. Three levels of slow forward speed of the tractor (I low gear, II low gear and III low gear) were selected. Seed canes were manually selected to avoid tearing,

Fig. 6 Field operation of sugarcane planter

overlengthening and producing other defective seed canes prior to the field test. The average diameter of the chosen seed canes was 28.47 mm in the a range of 20–39 mm. Compound fertilizer was used.

Evaluation of the Transversal Sugarcane Planter

The performance of the transversal sugarcane planter was evaluated in terms of furrow depth, stability of furrow depth, seeding depth, seeding interval, seed uniformity and fertilization interval.

Rotary Tillage Power for Laboratory (kw)

$$P = 1.73 \cdot \mathrm{U} \cdot \mathrm{I} \cdot \cos\varphi, \varphi = 0.8$$

Stability of Furrow Depth (%)

$$\text{stability coefficient of furrow depth} = 1 - \frac{\sqrt{\frac{\sum_{i=1}^{n}(\text{furrow depth of i–th measuring point–average furrow depth})^2}{\text{total number of measuring points}-1}}}{\text{average furrow depth}} \times 100\%$$

Seeding Depth (cm)

$$\text{seeding depth} = \frac{\sum_{i=1}^{n}\text{seeding depth of the i} - \text{th measuring point}}{\text{total number of measuring points}}$$

Seeding Interval (cm)

The qualified index of seeding interval is important in evaluating the seeding performance. Here, the theoretical spacing of seed canes was 330 mm. Overlapping occurred when the actual seeding interval was less than 0.5 times that of the theoretical seeding interval (less than 165 mm). Missed seeding transpired when the actual seeding interval was greater than 1.5 times that of the theoretical seeding interval (greater than 495 mm). The qualified seeding interval was within the range of 165–495 mm.

Seed Uniformity (%)

Seed average interval, standard deviation and coefficient of variation were calculated as seed uniformity indicators.

$$\text{seed average interval} = \frac{\sum \text{seed interval}}{\text{total number of seeds}}$$

$$\text{standard deviation} = \sqrt{\frac{\sum(\text{seed interval} - \text{seed average interval})}{\text{total number of seeds}}}$$

$$\text{coefficient of variation} = \frac{\text{standard deviation}}{\text{seed interval}}$$

Fertilization Interval (mm)

The average fertilization interval was calculated as the fertilization interval to ensure that the seed cane and fertilizer have a certain distance to avoid seedling burning.

$$\text{average fertilization interval} = \frac{\sum_{i=1}^{n}\text{fertilization interval of the i} - \text{th measuring point}}{\text{total number of measuring points}}$$

Analysis

All experimental statistics were recorded in Excel 2016 to calculate the means and rate of change. Statistical analysis software SPSS was used for orthogonal analysis. Software Design-Expert was employed for the quadratic regression rotation orthogonal statistical analysis and two-factor response surface analysis. Analysis was performed at 1% level of significance.

Results and Discussion

The laboratory setup was constructed to identify the operational parameters. The effects of rotation speed, forward speed, chain inclination, sugarcane box inclination, cam speed and cam repose angle on the power of the rotary tiller, the seeding qualified rate and the fertilization interval during laboratory evaluation were discussed below.

Effect of Rotation Speed on Rotary Tillage

Shop debugging was used to preliminarily test the transmission characteristics and no-load operating conditions. The ratio of motor speed to rotary tillage speed corresponded to the transmission ratio of the gearbox at 1.8:1 (Table 2). The total power of rotary tillage increased with the rotary speed and was more than twice that of the single-group tillage. This finding indicated that the gearbox also consumed a certain power in the transmission and the power gradually increased with the speed (Table 2). The rotation speed of tillage should be in a rational range. A small rotation speed increased the cutting pitch, which in turn increased the resistance of the furrow and reduced the soil fragmentation rate. The required speed of the rotary tillage for furrowing is 200–300 r/min (Kang et al. 2016). Therefore, the output speed of the tractor was 540 r/min at 300 r/min rotary tillage speed.

Table 2 Analysis of the effect of rotation speed on tillage power

Motor speed (r/min)	Rotation speed of tillage (r/min)	Power of single tillage (kw)	Total power of rotary tillage (kw)
430	239	0.48	1.96
532	305	1.02	2.14
591	357	1.06	2.43
654	403	1.2	2.49
720	452	1.19	2.61

Effect of Sprocket Speed, Chain Inclinations and Sugarcane Box Inclination on Seeding Qualification Rate

The seeding interval was determined by the seeding sprocket speed, which is influenced by the speed of the ground wheel depending on the forward speed of the tractor. A simple seeding test platform was used to select the best sprocket speed. The relationship between the sprocket speed and qualified rate was fitted (Fig. 7). Statistical analysis showed that the qualification rate of the seeding unit increased first and then decrease with the increasing sprocket speed (Yazgi et al. 2014). This phenomenon occurred because the overlapping rate decreased and the missing rate increased with the sprocket speed (Fig. 7).

Table 3 shows that the effect of sprocket speed and chain inclinations on seeding qualification rate was significant, but that of seed cane box inclination was non-significant. Orthogonal statistical analysis indicated that the optimal angle of the conveyor chain inclination angle, the inclination angle of the seed cane box and the sprocket speed were 55°, 45° and 9.16 r/min respectively. Therefore, I low gear of the tractor forward speed was selected according to the speed conversion and the diameter of the ground wheel (700 mm).

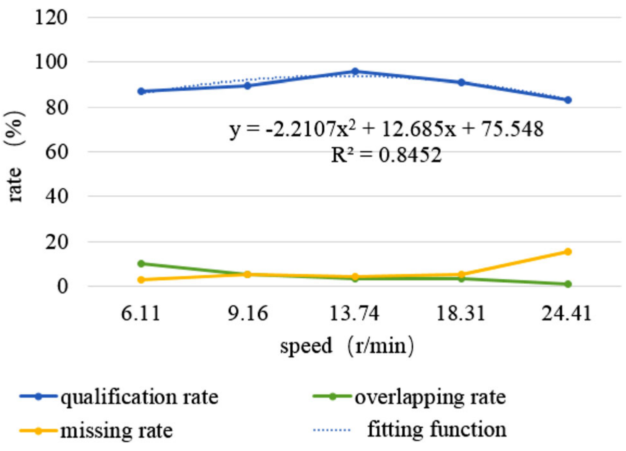

Fig. 7 Effect of speed on seeding

Effect of Forward Speed, Camshaft Speed and Camshaft Repose Angle on Fertilization Interval

Quadratic regression rotation orthogonal analysis indicated that the fertilization interval was significantly affected by forward speed, camshaft speed and camshaft repose angle (Table 4). The constraints were the tractor's walking speed in 0.8 m/s, the cam's repose angle range of 20–100°, the camshaft speed range of 100–140 r/min and the fertilization interval of 100–130 mm. The regression equation of the fertilization interval was used as the objective function. The optimal values for the rotation speed of the cam shaft, cam's repose angle and forward speed were 137 r/min, 38 and 0.8 m/s, respectively, as calculated by software Design-Expert. Hence, the average fertilization interval was approximately 120 mm, and the gear ratio between the ground wheel shaft and the cam shaft was 6.2:1.

Field Evaluation of the Planter

After the parameters were selected in the laboratory evaluation, the transversal double-bud sugarcane planter was tested in the field.

Effect of Forward Speed at 540 r/min Output Speed of the Tractor on the Stability of the Furrow Depth

The two-factor response surface curve (Fig. 8) showed that the stability of the furrow depth decreased with the increasing forward speed or furrow depth. The increasing soil backflow with the forward speed reduced the stability of the furrow depth (Table 5). The furrowing stability of the test was above 89%, which satisfied the requirements of the qualification rate of the furrow depth and indicated that the opener had certain furrow reliability.

Evaluation of Seeding Performance

The seeding performance was evaluated by planting 100 sugarcanes each time in three repeated field trials (Fig. 9). The seeding depth range of 20.8–21.8 cm was smaller than the furrowing depth of 30 cm (Table 5) because the time

Table 3 ANOVA for the effect of different parameters on seeding qualification rate

Level	1	2	3	4	5
Sprocket speed	6.11 r/min	9.16 r/min	13.74 r/min	18.31 r/min	24.41 r/min
Chain inclinations	45°	50°	55°	60°	65°
Cane box inclinations	35°	45°	55°	65°	75°
ANCOVA	–	–	–	–	–
Factor	df	*p*	–	–	–
Sprocket speed	4	4.55×10^{-5}***	–	–	–
Chain inclinations	4	5.45×10^{-15}***	–	–	–
Cane box inclinations	4	1.34×10^{-1}	–	–	–

***significant ($P < 0.01$).

Table 4 Analysis of quadratic regression rotation orthogonal for the effect of different parameters on fertilization interval

Level	1	2	3	4	5
Forward speed	0.6 m/s	0.68 m/s	0.8 m/s	0.92 m/s	1 m/s
Cam speed	140 r/min	132 r/min	120 r/min	108 r/min	100 r/min
Cam repose angle	20°	36°	60°	84°	100°
Quadratic regression rotation orthogonal	–	–	–	–	–
Factor	df	*p*	–	–	–
Forward speed	1	< 0.0001***	–	–	–
Cam speed	1	< 0.0001***	–	–	–
Cam repose angle	1	< 0.0001***	–	–	–

interval between furrowing and seeding caused the soil, which was thrown by the rotary tillage to fall back into the trench formed by the rear plough. Hence, the seeding depth was reduced. The seeding qualified rate was 91%, and the coefficient of variation was 0.31% (Table 5). The average interval was in the range of 40.91–41.71 mm (Table 6), and most of the seeding intervals were within a reasonable range of 330–495 mm (Fig. 10). This value was slightly larger than the theoretical interval because the ground wheel sunk when furrowing, thereby reducing the rotation radius of the ground wheel, increasing the sprocket speed and affecting the seeding interval. However, the actual interval satisfied the requirements of precise planting. Thus, the transversal planting method can effectively avoid seed overlapping, reduce seed consumption and effectively prevent missing seedlings.

Evaluation of Fertilization Performance

The fertilization interval was within 113.5–117.1 mm (Table 4) at the forward speed I low to III low, which was even and almost similar due to the synchronous changing of the forward speed and the cam speed. The increase in the forward speed also increased the forward distance and the cam speed, resulting in the unchangeable fertilization interval.

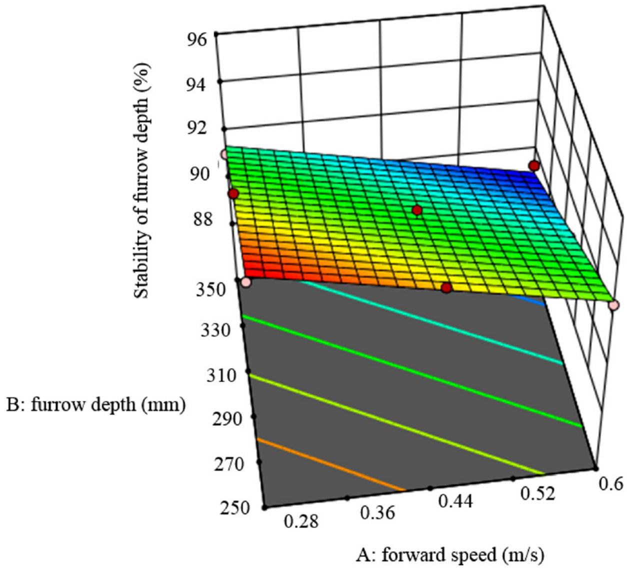

Fig. 8 Response surface curve of furrow depth stability

Table 5 Effect of the forward speed on the stability of the furrow depth and the fertilization interval

Forward speed (m/s)	Theoretical furrow depth (mm)	Stability of furrow depth (%)	Fertilization interval (mm)
I low	250	95.0	113.5
I low	300	93.8	
I low	350	91.1	
II low	250	94.0	117.1
II low	300	92.4	
II low	350	89.9	
III low	250	92.6	114.7
III low	300	90.6	
III low	350	89.3	


(a) (b)

Fig. 9 View of 250 furrow depth (**a**) and 300 furrow depth (**b**)

Table 6 Seeding depth and qualification rate of the planter

	Average interval (cm)	Seeding depth (cm)	Standard deviation	Coefficient of variation	Qualification rate (%)	Total coefficient of variation	Total qualification rate (%)
1	41.05	20.8	11.56	0.28	92	0.31	91
2	40.91	21.6	10.12	0.25	93		
3	41.71	21.8	16.94	0.41	87		

Economic Analysis of the Pre-cut Sugarcane Transversal Planter

Traditional sugarcane planting is expensive because the cost of seed canes accounts for approximately 20% of the total cultivating cost (Patnaik et al. 2016). Seed cane consumption is approximately 4.4 t/ha for the transversal double-bud sugarcane planter and 9–18 t/ha for traditional planting, which relies on a large amount of seed canes to ensure a high germination rate. The proposed planter showed 51–75% reduction of seed canes compared with the traditional method. The labour involved in planting was also considerably decreased.

Conclusions

A novel transversal double-bud sugarcane planter with seed pre-cutting was designed, and its properties were investigated during field trials. The following results were obtained:

(1) The planter had above 89% furrow depth stability at 540 r/min output speed of the tractor, indicating its good furrowing reliability.
(2) The seeding depth of 20.8–21.8 cm was less than the furrowing depth of 30 cm. The qualification rate of the seeding unit increased first and then decreased with the increasing sprocket speed. The qualified rate of seeding was 91%, and the seeding interval was

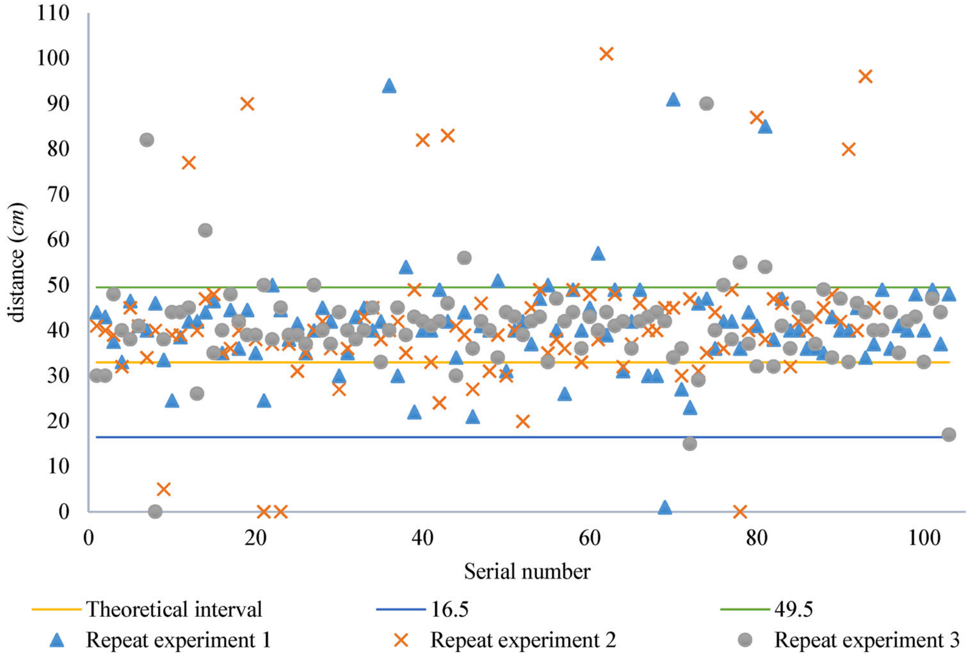

Fig. 10 Effect of the seeding interval

within a reasonable plant interval range of 330–495 mm. Hence, the accurate transversal seeding of double-bud seed canes was achieved.

(3) The seed consumption for this planter was approximately 4.4 t/ha, which was 51–75% lower than that for the traditional method.

(4) The fertilization interval was substantially affected by forward speed, camshaft speed and camshaft repose angle. Its value was stable at 113.5–117.1 mm when the cam's repose angle was 38°, and the forward speed was in I–III low gear.

Acknowledgements The authors thank Tian-Xiang Liu, Yun-Fa Yu and Zhong-Bin Wang for their valuable help in the investigation.

Authors' Contributions Jia-Qin Zhong, Fang-Lan Ma and Yuan-Lin Chen performed analysis on all samples, interpreted data and wrote the manuscript. Shang-Ping Li and Li-Min Tao helped to evaluate and edit the manuscript. All the authors read and approved the final manuscript.

Funding This study was supported by Project of Guangxi Science and Technology (grant no. AB18281016), Project of State Key Laboratory for Conservation and Utilization of Subtropical Agro-bioresources (grant no. SKLCUSA-b201706), Innovation Project of Guangxi Graduate Education (grant no. YCBZ2020035) and Initiation Project of Introducing Talents for Scientific Research of Beibu Gulf University (grant no. 2019KYQD34).

Compliance with Ethical Standards

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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