DESIGN AND EXPERIMENT OF NO-TILLAGE PRECISION PLANTERS WITH STAGGERED SEEDLING BELTS FOR SOYBEAN
/
交错苗带式大豆精量免耕播种机设计与试验

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ABSTRACT
According to the requirements of soybean stripping planting in the Huang-Huai-Hai region, a new planting mode was proposed, and a no-tillage staggered seedling belt soybean precision planter was designed. A seed-metering device with staggered distribution of sockets was designed. The optimal parameter combination was obtained through simulation analysis, and its structural rationality was verified through bench experiments. It achieved staggered seedling belt seeding; a retractable top rod seeding device was designed to improve seeding efficiency; the arrangement of the rotary cutter for the seedling belt cleaning and preparation device was designed to reduce work energy consumption. The field experiment results showed that when the forward speed was 8 km/h, the reliability and trafficability of the no-tillage staggered seedling belt soybean precision planter were qualified. The qualified rate of sowing depth was 92.6%, the qualified rate of grain spacing was 94.4%, the leak sowing rate was 1.8%, the repeat sowing rate was 38%, the seed exposure rate was 0.74%, and the operation efficiency was 1.92 hm²/h.

摘要
针对黄淮海地区的大豆带状种植要求，本文提出一种新的种植模式，并设计了一种交错苗带式大豆免耕精量播种机。设计了一种窝眼交错分布的排种器，仿真分析得出最佳参数组合，并通过台架试验验证了其结构合理性，实现了交错苗带播种；对苗带清理整备装置的旋刀的排布进行设计，减少了工作能耗。田间试验结果表明：当前进速度为 8km/h 时，交错苗带式大豆免耕精量播种机可靠性合格，通过性良好。播深合格率为 92.6%,粒距合格率为 94.4%,漏播率为 1.8%,重播率为 3.8%,晾籽率为 0.74%,作业效率为 1.92hm²/h。

INTRODUCTION
Narrow-row-dense-planting, as a soybean planting technique, has a large application area in soybean cultivation internationally *(Chian Statistic Press, 2022; Yao, 2015; Ding et al., 2005)*. The practice has shown that compared to traditional planting techniques, narrow-row-dense-planting techniques can increase yield by more than 15% *(Zhang et al., 1995)*. China proposes to demonstrate and promote soybean strip planting technology in the Huang-Huai-Hai region. At present, the Huang-Huai-Hai region is mostly characterized by equal-width-row-planting and narrow-row-dense-planting. It lacks a unified planting mode that combines dense-planting and strip-planting, as well as corresponding planting machine models *(Zhang et al., 2011)*.

Regarding the soybean planting mode, foreign scholars have conducted research for a long time. Cooper *(Cooper, 1977)*, from the United States, proposed a high-yield "SSS" model for soybeans by reducing row spacing to achieve narrow-row-dense-planting. And the theoretical level and technology of soybean planters in European and American countries are already relatively mature. Foreign planters generally integrate machinery, electricity, fluid, and gas, and combine algorithms to achieve intelligent control of seeding, improving the quality of seeding operations and achieving large-scale operations *(Ale et al., 2023; Karayel et al., 2022; Zavrazhnov et al., 2023)*. A lot of research and exploration have also been conducted on precision seed-metering device. Wright F. S *(Wright et al., 1995).* designed and invented a seeding mechanism with variable particle spacing, and the seeds discharged from it are distributed in a zigzag shape on the seedbed. The Pro Max 40 suction seed-metering device developed by John Deer can adapt to various sizes of seeds by improving the shape of the mold hole, while reducing the vacuum required for the air chamber *(Giannini et al., 1995)*.

Domestic scholars have also conducted related explorations. Chen Wei et al. *(Chen et al., 2019).* designed an air-blown anti-blocking soybean no-tillage planter, which uses a blower fan to blow straw onto the back ridge to achieve no-tillage in a clean area. However, the cleaning effect is not good when the soil moisture is high; Wang Chaoqun et al. *(Wang et al., 2018).* designed a crop removal and no-tillage soybean planter, which uses a combination of moving and fixed blades to clean the straw in the sowing area. However, this machine has high vibration, high energy consumption, and certain safety hazards. Chen Meizhou et al. *(Chen et al., 2018).* designed a single-disc double-row air suction seed-metering device for soybean narrow-row-dense-planting. It uses a seed-metering device with inner and outer double-ring suction holes and a seed splitter to achieve double-row seeding. However, the air suction seed-metering device is expensive and prone to blockage caused by the suction of floating debris during operation, making it unable to work properly.

In response to the lack of a planting mode that combines dense planting and strip sowing in the Huang-Huai-Hai region, this article proposes a staggered seedling belt planting mode. As shown in Figure 1, the width of the seedling belt in this planting mode is 150 mm, and the seeds on the same seedling belt are arranged in a staggered manner. The distance between the two seedling belts is 450 mm, and the distance between two adjacent seeds on the same side of the seedling belt is 140 mm. This planting mode improves ventilation and lighting effects, facilitates plant absorption of nutrients such as water and fertilizer, and increases soybean yield *(Liu et al., 2011; Qi et al., 2013; Yao et al., 2020)*. At the same time, the row spacing is the same as the required row spacing for corn sowing, which can achieve universal use for corn and soybeans. In response to the planting mode and the existing problems of the soybean planters, a staggered seedling belt-type soybean no-tillage precision planter was designed. Its key components were theoretically studied and structurally designed. The working performance of the planter was verified through field experiments, achieving the combination of agronomy and agricultural machinery.

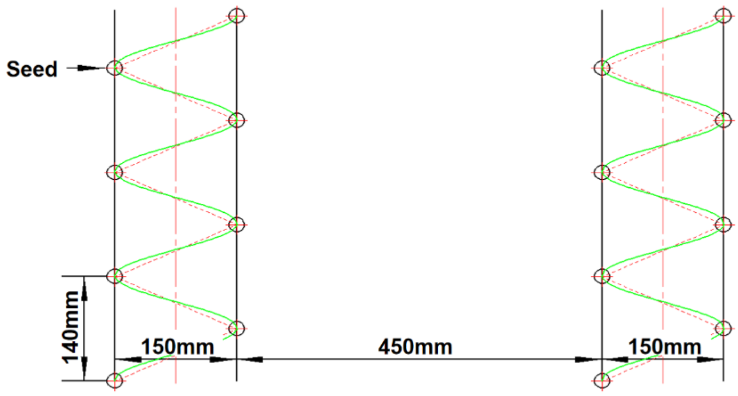

Fig. 1 - Staggered seedling belt planting pattern

MATERIALS AND METHODS

The structure and working principle

The staggered seedling belt type soybean no-tillage precision planter mainly consists of a suspension device, a frame, a depth limiting wheel, a seedling belt cleaning and preparation device, a fertilizer colter, a fertilizer box, a seedbox, a seed opener, a staggered seedling belt type seed-metering device, a cage-type earth covering pressing wheel, etc. The planter is equipped with four sowing units, with a distance of 600 mm between each sowing unit. Its structure is shown in Figure 2.

During operation, the planter is connected to the tractor through a suspension device and moves forward under the traction of the tractor. The ground wheel plays a depth-limiting role, limiting the depth of the operation. The fertilizer ditch is opened by the fertilizer colter. At the same time, the power output of the tractor provides power to the seedling belt cleaning and preparation device, driving it to clean and prepare the seedling belt. After the seedling belt cleaning and preparation are completed, the seed opener opens the seed ditch. The planter drives the cage-type earth-covering pressing wheel to rotate forward while providing power to the staggered seedling belt metering device and fertilizer applicator through the transmission mechanism to complete the seeding and fertilization. Finally, the cage-type earth-covering pressing wheel is used for soil covering and compaction. The main technical parameters of this planter are shown in Table 1.

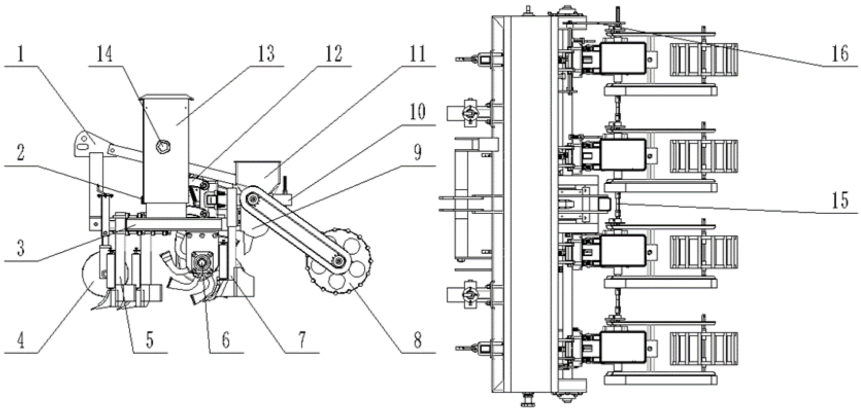

Fig. 2 - Schematic diagram of the structure of the staggered seedling belt type soybean no-tillage precision planter

1. Suspension device; 2. Gearbox; 3. Frame; 4. Depth-limiting wheel; 5. Fertilizer colter; 6. Seedling belt cleaning and preparation device; 7. Seed opener; 8. Cage-type earth-covering pressing wheel; 9. Staggered seedling belts seed-metering device; 10. Planting unit rack; 11. Seedbox; 12. Profiling mechanism; 13. Fertilizer box;14. Fertilization adjustment device; 15. Card gear; 16. Chain transmission gearing.

Table 1

Primary technical parameters

Parameters	Numerical value
Dimensions（length×width×height）/（mm×mm×mm）	1800×2400×1430
Auxiliary power / kW	88~103
Hang	Three-point linkage
Rows	4
Working width / m	2.4
Sowing depth / mm	20~40
Width of staggered seedling belt / mm	150
Qualified rate of seed spacing / %	≥90
Seed interlocking qualification rate / %	≥90

Critical Component Design

Structure and working principle of the seed-metering device

The seed-metering device, as the core component of the planter *(Zhang et al., 2004).*, is the key to achieving staggered seedling belts. To achieve staggered seedling belt planting, a staggered seedling belt metering device is designed, mainly composed of a seed-metering device shell, a socket wheel, a telescopic ejector rod, an ejector rod installation wheel, a seed feeding block, a seed removal brush, a seed protection belt shaft, a flexible seed protection belt, a seed splitter, etc. Its structure is shown in Figure 3.

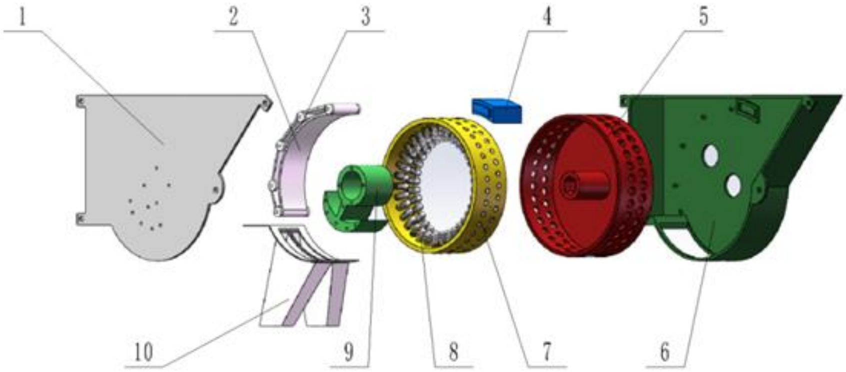

Fig. 3 - Structure diagram of staggered seedling belt seed-metering device

1. Upper shell of seed-metering device; 2. Flexible seed protection belt; 3. Seed protection belt shaft; 4. Seed removal brush; 5. Socket wheel; 6. Lower shell of the seed-metering device;7. Ejector rod installation wheel; 8. Telescopic ejector rod; 9. Seed feeding block;10. Seed splitter;

As shown in Figure 4, the staggered seedling belt metering device consists of a seed filling area, a seed cleaning area, a seed protection area, a seed discharge area, and a reset area. When the seed-metering device is working, the seeds enter the seed chamber from above. Then they are squeezed into the socket by their gravity and the pressure between the seeds. As the socket wheel rotates, the excess seeds in the socket are brushed off by the seed removal brush, and one seed is retained in the socket. Then, the seeds come to the seed discharge area under the protection of the flexible seed protection belt. The seeds in the seed discharge area are thrown out of the socket due to their gravity and the push of the telescopic ejector rod, completing the seeding process.

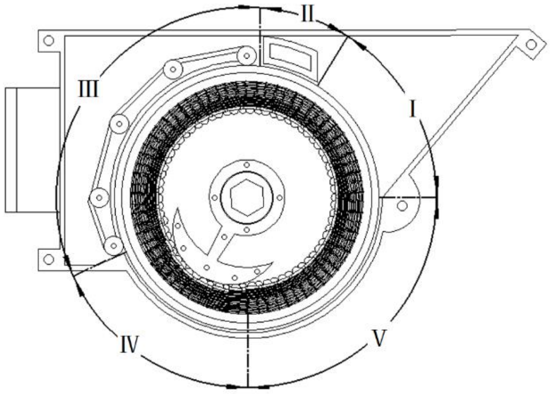

Fig. 4 - Zoning diagram of seed metering device

Ⅰ. Seed filling area; Ⅱ. Seed clearing area; Ⅲ. Seed protection area; Ⅳ. Seed discharge area; Ⅴ. Reset area;

Design of socket wheel

The socket wheel is a key component of the seed-metering device to achieve precision seeding. It was designed because it has a significant impact on the repeat sowing index, leak sowing index, and other factors of the seed-metering device. There are two rows of sockets on the socket wheel, with 35 in each row. The sockets are arranged in a staggered manner to ensure that the seeds are distributed in a staggered manner on the seedling belt. Related studies have shown that the best filling effect is achieved when the diameter of the socket is 1.64 times the average seed diameter *(Dun et al., 2016)*. Therefore, the diameter of the socket is determined to be 12.8 mm and the depth of the socket is 9 mm. The diameter of the socket wheel is designed to be 280 mm. To facilitate seed filling, the chamfer angle of the socket is designed to be 45°. Based on experience, take 35 sockets.

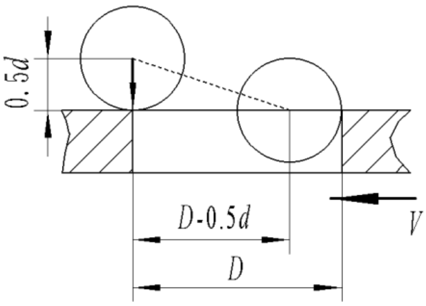

Fig. 5 - Soybean filling process

D - Socket diameter; d - Seed average diameter; V - The relative velocity between the socket and the seed

As shown in Figure 5, analyze the movement between the seed and the socket. When the socket rotates, the center of mass of the seed is on the outer circumference of the socket wheel. When the socket speed reaches a certain value, the seed will slide over the socket, causing missed seeding. At this time, the socket speed is called the limit speed. The necessary condition for smooth seeding is that the socket speed does not exceed the limit speed. The vertical displacement of the seed is 0.5d, the time is t. There is the following relationship:

$$\frac{d}{2}=\frac{gt^2}{2} \tag{1}$$

When the seed can be smoothly filled, the maximum linear velocity at the socket is V_{max}, and the displacement of the seed in the horizontal direction is:

$$D-\frac{d}{2}=V_{max}t \tag{2}$$

According to equations (1) and (2):

$$V_{max}=\left(D-\frac{d}{2}\right)\sqrt{\frac{g}{d}} \tag{3}$$

The condition for successfully completing seed filling is (4). Substitute it into (3):

$$v_1 \le V_{max} \tag{4}$$

$$\frac{2\pi rn}{60}\le\left(D-\frac{d}{2}\right)\sqrt{\frac{g}{d}} \tag{5}$$

It can be concluded that:

$$n\le\frac{60}{2\pi r_w}\left(D-\frac{d}{2}\right)\sqrt{\frac{g}{d}} \tag{6}$$

where:

v_1 - Linear speed of socket wheel, (m/s);
D - Socket diameter, (mm);
D - Seed average diameter, (mm);
G - Gravitational acceleration, (m/s²);
r_w - Socket wheel radius, (mm);
n - Socket wheel speed, (r/min);

According to equation (6), it can be seen that when the average diameter of seeds and the radius of the socket wheel are constant, the speed of the socket wheel is proportional to the diameter of the socket. To ensure that seeds can be filled smoothly under all socket diameters, the minimum socket diameter is selected to calculate the maximum speed of the socket wheel. When the radius of the socket wheel is 120 mm, the diameter of the socket is 12 mm. When the average seed diameter is 7.31 mm, the rotational speed of the socket wheel calculated according to equation (6) should not exceed 24.3 r/min. Based on practical experience, the distance between the two rows of sockets on the designed socket wheel is 27 mm, and the thickness of the socket wheel is 70 mm. Based on the above data, the structure of the socket wheel is shown in Figure 6.

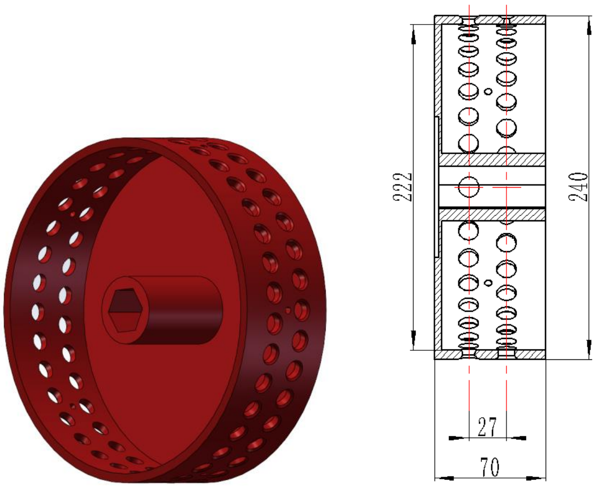

Fig. 6 - Structure diagram of socket wheel

Simulation test

Select the diameter of the socket, the length of the chamfered edge of the socket, and the rotational speed of the socket wheel as the experimental factors. Select the qualified index, repeat sowing index, and leak sowing index as performance evaluation indicators. The simulation experiment was conducted using a three-factor five-level quadratic regression orthogonal rotation combination design method *(Yu et al., 2011)*, and the experimental code is shown in Table 2.

During the simulation experiment, a total of 23 sets of experiments were conducted, including 14 sets of analysis points and 9 sets of zero points. Each set of experiments was repeated 3 times, and the average value was taken as the experimental result.

Table 2

Test factor coding table

Numbers	Factors		
	Socket wheel speed X1 (r/min)	**The chamfer edge length of socket X2 (mm)**	**Socket diameter X3 (mm)**
1.682	23.8	2.5	14
1	22.5	2.21	13.6
0	20.4	1.5	13
-1	18.3	0.79	12.4
-1.682	17	0.5	12

Experimental results were obtained through experiments. The experimental results were input into Design-Expert for data analysis and regression fitting *(Jia et al., 2021*). By conducting variance analysis on the qualified index, repeat sowing index, and leak sowing index, and removing insignificant factors, the regression equations between each indicator and each factor are obtained as follows:

$$Y_1 = 93.72 - 0.79X_1 + 0.78X_2 - 0.44X_3 - 0.62X_1X_2 - 1.48{X_1}^2 - 1.84{X_2}^2 - 1.00{X_3}^2 \quad (7)$$

$$Y_2 = 3.56 - 1.43X_1 + 0.82X_2 + 1.42X_3 + 0.64{X_2}^2 + 0.76{X_3}^2 \quad (8)$$

$$Y_3 = 2.83 + 2.22X_1 - 1.60X_2 - 0.99X_3 + 1.21{X_1}^2 + 1.22{X_2}^2 \quad (9)$$

By using the dimensionality reduction method, one of the parameters of the socket wheel speed, socket chamfer edge length, and socket diameter was adjusted to zero. A response surface graph was drawn to show the interaction between the other two factors on each indicator. Through response surface analysis, it was found that within the range of socket chamfer edge length of 0.5~2.5 mm, socket wheel rotation speed of 17~23.8 r/min, and socket diameter of 12~14 mm, optimization solution is carried out under the condition of maximizing the qualified index and minimizing the repeat sowing index and leak index. The optimal parameter combination of the seed-metering device is obtained as follows: the chamfer length of the socket is 1.5 mm, the socket wheel speed is 20.2 r/min, and the socket diameter is 12.8 mm. At this time, the qualified index is 93.92%, the repeat sowing index is 3.57%, and the leak sowing index is 2.51%.

Design of seedling belt cleaning and preparation device

To ensure the quality of soybean sowing, it is necessary to clean and prepare the operating area. To reduce work resistance, reduce energy consumption, and improve the stability of the machine body during operation, a seedling belt cleaning and preparation device was designed. The device is composed of a knife shaft, a tool magazine, a curved knife, and a straight-faced curved knife. Its structure is shown in Figure 7. The seedling cleaning and preparation device is divided into four knife groups, each corresponding to a seedling belt. The width of the knife group is greater than the width of the seedling belt, and 200 mm is taken. Each knife set includes two straight-faced curved knives on both sides and two curved knives in the middle. The two curved knives in the middle clean and prepare the seedling belt while also cleaning the middle area of the seed opener to prevent blockage. Straight-faced curved knives and curved knives are arranged in a staggered manner. The angle between two straight-faced curved knives in the same cutting group is 180°, and the angle between two curved knives is 180°. The specifications of the rotary knives are all IT245, and their arrangement is shown in Figure 8. Through kinematic analysis, it is determined that the rotational speed of the rotary cutter should be greater than or equal to 379 r/min;

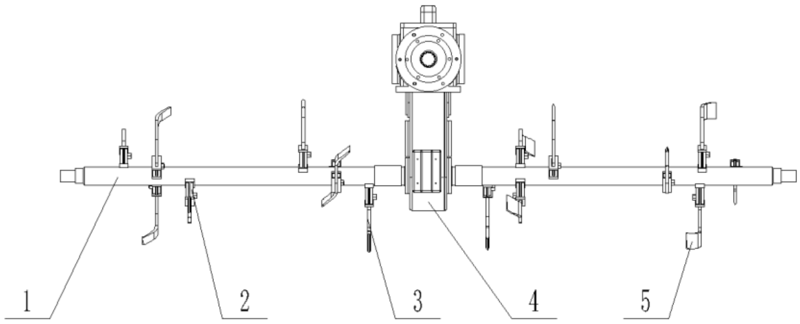

Fig. 7 - Seedling belt cleaning and preparation device
1. Knife shaft; 2. Tool magazine; 3. Straight-faced curved knife; 4. Transmission; 5. Curved knife

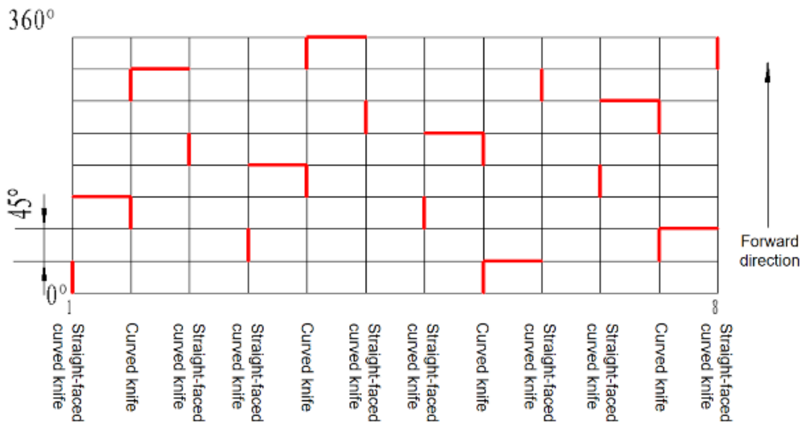

Fig. 8 - Rotary knife arrangement

RESULTS

Bench experiment

To verify the simulation test results, a prototype of the seed-metering device was manufactured according to the optimal parameters obtained from the simulation test, and the seed-metering device bench experiment was carried out, as shown in Figure 9.

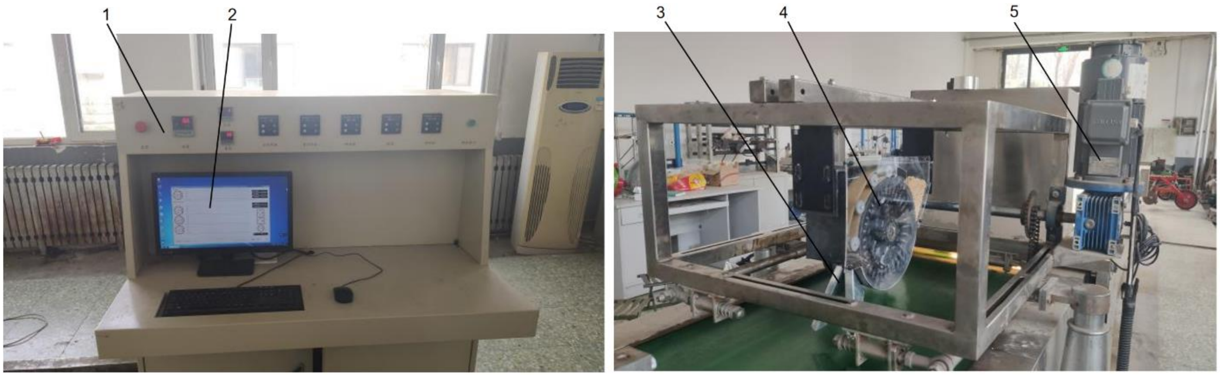

Fig. 9 - Bench test of seed metering device
1. JPS-12 electrical control cabinet; 2. Monitoring and detection software; 3. Staggered seedling belts metering device; 4. Seed splitter; 5. Drive motor

The experiment was conducted on the JPS-12 type seed-metering device performance testing platform, selecting Zhong-Huang13 soybean seeds as the experimental seeds. Before the experiment, the seed-metering device speed was set to 20.2 r/min. Based on the relationship between the theoretical grain spacing, the number of plants per mu, and the number of sockets, the corresponding conveyor belt speed was calculated to be 1.65 m/s. In the experiment, seeds on the conveyor belt after stable seeding were selected for measurement, and their qualified index, repeat sowing index, and leak sowing index were calculated. The experiment was repeated for 5 groups, and the average value was taken as the final result. The experimental results are shown in Table 3.

Table 3

Bench test results

Numbers	Qualified index（%）	Repeat sowing index（%）	Leak sowing index（%）
1	94.02	3.66	2.32
2	93.28	4.13	2.59
3	93.66	3.33	3.01
4	93.37	3.59	3.04
5	93.89	3.57	2.54
Average value	93.64	3.66	2.70

The experimental results showed that the qualified index of the seed-metering device was 93.64%, the repeat sowing index was 3.66%, and the leak sowing index was 2.70%. The difference between the experimental results and the theoretical results was within a reasonable range, proving the reliability of the simulation test data. All indices in the experiment meet the industry standard requirements, indicating that the structure of the staggered seedling belt seed-metering device is reasonable.

Field experiment

The experiment was conducted on June 21, 2021, in Linzi, Shandong Province, as shown in Figure 10. The previous crop in the experimental field was wheat, and the height of machine-harvested stubble was 190 mm. The tractor model was KAT-1404, and the operating speed of the prototype was 8 km/h. The soybean variety selected for the experiment was Zhong-Huang 34. Refer to GB/T6973-2005 "Test Methods for Single Seed (Precision) Planter " for the experiment.

Fig. 10 - Field test diagram

The experimental prototype did not experience any malfunctions or blockages during the operation process. The reliability of the equipment is qualified. Calculate the various data of field experiments on the experimental prototype, and the experimental results are shown in Table 4

Table 4

Test results

Numbers	Sowing depth qualification rate (%)	Grain spacing qualification rate (%)	Leak sowing rate (%)	Repeat sowing rate (%)	Seed exposure rate (%)
1	91.8	94.5	1.6	3.9	0
2	93.1	92.8	2.5	4.7	1.2
3	92.7	94.1	2.2	3.7	0
4	92.9	95.2	1.3	3.5	0.9

Numbers	Sowing depth qualification rate (%)	Grain spacing qualification rate (%)	Leak sowing rate (%)	Repeat sowing rate (%)	Seed exposure rate (%)
5	92.5	95.4	1.4	3.2	1.6
Average value	92.6	94.4	1.8	3.8	0.74
Standard value	80.0	75.0	10.0	20.0	2.0
Conclusion	Qualified	Qualified	Qualified	Qualified	Qualified

From Table 4, it can be seen that at a forward speed of 8 km/h, the sowing depth qualification rate is 92.6%, the grain spacing qualification rate is 94.4%, the leak sowing rate is 1.8%, the repeat sowing rate is 3.8%, the seed exposure rate is 0.74%. The experimental indicators are all better than the industry standard requirements. The forward speed of the experimental prototype during operation is 8 km/h, the operating width is 2.4 m, the operating length is 24 km, and the operating efficiency is 1.92 hm^2/h, which meets the operating requirements.

CONCLUSIONS

(1) A new soybean planting model suitable for the Huang-Huai-Hai region has been proposed. The theoretical spacing of this model is 140 mm, and the width of the seedling belt is 150 mm. The seeds on the same seedling belt are arranged in a staggered manner, and the distance between the two seedling belts is 450 mm, which improves the growth conditions of crops. A staggered seedling belt type soybean no-tillage precision planter was designed, and its structural layout was designed. Based on the planting mode, the operating row spacing was determined to be 600 mm, the operating width to be 2.4 m, the seedling belt width to be 150 mm, and the sowing depth to be 20-40 mm.

(2) A staggered seedling belt metering device was designed, and simulation experiments on the seeding process were conducted. The optimal parameters after data processing were obtained: the diameter of the socket was 12.8 mm, the chamfered edge length of the socket was 1.5 mm, the depth of the socket was 9 mm, the diameter of the socket wheel was 280 mm, and the speed of the socket wheel was 20.2 r/min. Its structural rationality was verified through bench tests, achieving staggered seedling belt seeding. The seedling belt cleaning and preparation device has been designed, and the distribution mode of the rotary blade has been determined to be a staggered arrangement of straight-faced curved blades and curved blades. It was been determined that the blade shaft speed needed to be greater than 379 r/min.

(3) Through field experiments on the planter, the reliability of the staggered seedling belt soybean no-tillage precision planter is qualified, the machine passability is qualified, and meets the industry standard requirements.

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