DESIGN AND EXPERIMENT OF SWING TYPE SYNCHRONOUS MULCHING FOR RICE DIRECT SEEDER
/
悬摆式同步覆土水稻直播机的设计与试验

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ABSTRACT
In order to solve the problem of mechanical direct seeding of rice seeds on the exposed soil surface, which is affected by bird and mouse damage, rain and sun exposure, etc., a pendulum-type synchronous soil-covered rice direct seeding machine was developed. In order to clarify the leakage and anti-entanglement performance of the mulching plate, linear function type, quadratic function type and exponential function of the sliding blade mulching plate were designed, and the mulching plate structure, straw distribution spacing and suspension rotation speed were used as independent variables. Using straw entanglement rate and straw interference rate as evaluation indicators, a full-factor experimental study was carried out to determine the optimal structure of the mulching plate; a pendulum-type synchronous soil covering live broadcast EDEM simulation model was established, and field experiments were conducted to verify its synchronous soil covering performance. The test results show that the exponential function of the sliding blade mulching plate has the best performance, and the soil covering rate of the three soil covering plate structures is 87.37~98.54 under the conditions of forward speed 0.6~1.0 m/s and suspension rotation speed 90~150 r/min. %, the covering soil thickness is 5.08~5.84 mm. This research can provide reference for rice mechanical direct seeding technology and equipment.

摘要
水稻机械直播稻种裸露土壤表面，易受周围环境和气候等影响，造成出苗率降低，针对此问题，研制了一种悬摆式同步覆土水稻直播机。为了明确覆土板的漏覆和防缠性能，设计了一次函数型、二次函数型和指数函数型滑刃式覆土板，并以覆土板结构、秸秆分布间距和悬摆转速为自变量，将秸秆缠挂率和秸秆干扰率为评价指标，开展了全因素试验研究，确定最优覆土板结构；为了分析覆土板与土壤之间的相互作用，建立悬摆式同步覆土直播 EDEM 仿真模型，并通过开展田间试验验证其同步覆土性能。试验结果表明：指数函数型滑刃式覆土板性能最佳，且三种覆土板结构在前进速度为 0.6~1.0m/s 和悬摆转速 90~150r/min 条件下，覆土率为 87.37~98.54%，覆土厚度为 5.08~5.84mm。该研究可为水稻机械直播技术与装备设计提供参考。

INTRODUCTION
Rice is an important crop in the world, and mechanical direct seeding technology was a simple and effective cultivation method for saving labor, time and seeds (*Wan et al., 2021; Wang et al., 2020*). In particular, the advantage of row sowing and hole sowing could improve the yield *(Jang et al., 2021; Sansen et al., 2019; Sugirbay et al., 2020)*, and planting trenches and ditches could promote lodging resistance and population quality of rice (*Shu et al.,2010; Chen et al., 2021*). With the development of rice mechanical seeding technology, the advantages had been accepted by most farmers (*Pitoyo et al., 2021*). *Luoet al. (2007)* firstly developed mechanical direct seeding technology for ditching furrows and building ridges, and designed the direct seeder. Studies had shown that the yield of rice mechanical direct seeding was higher than manual sowing and UAV sowing *(Zhang et al., 2017; Singh et al., 2023)*. The direct seeder was sowing in furrows without mulching. The environment and climate would affect the seedling emergence and uniformity of double-cropping rice at low temperatures (*Hiroei et al., 2021, Yu et al., 2020*). Synchronous mulching technology could improve the emergence rate of basic seedlings and effective spikes in the field by using the rice dry direct seeding technology *(Youichi et al., 2019; Xu et al., 2014; Wang et al., 2016)*.

Liet al. (2020) developed a no-till seeding method of mulching rice stubble with a drill seeder, and *Zeng (2019*) used a precision hole drill of rice furrow fertilization in a dry drill. *Makangeet al. (2020)* and *Mudarisovet al.* (*2022*) predicted the cutting force and soil characteristics through discrete element simulation. They also studied the discrete element modeling of contact model particle parameters in wet soil. In addition, the element model of mulching equipment and ditching soil was established (*Pue et al., 2019; Lu et al., 2023*). Direct seeding fields had a high water content and fluidity, and wet direct seeding was generally adopted in southern China. However, there were few technologies and equipment for synchronous mulching *(Cheng et al., 2021; Zhang et al., 2023)*. To improve the anti-risk ability of rice, a synchronous mulching technology of wet direct seeding was studied. The results showed that different mulching depths and rice varieties had a great influence for seedling emergence, and the depth of seeds mulching with 5~10 mm soil was great (*Yu et al., 2020*). Then the sliding blade structures of mulching plates were introduced to reduce the twisting and interference of rice stubble. Finally, the swing synchronous mulching for rice direct seeder was designed and its performance was verified in the field.

MATERIALS AND METHODS

Swing type synchronous mulching direct seeder

Swing synchronous mulching of rice direct seeder was designed based on the power chassis of high speed seedling transplanter, the precision metering device of rice, the ditching and ridging equipment, the transmission system, and the swing synchronous mulching of equipment. The power of the high-speed seedling transplanter is provided to the measuring device and covering equipment by the transmission shaft, gear head, chain and axle sleeve as shown in Fig.1.

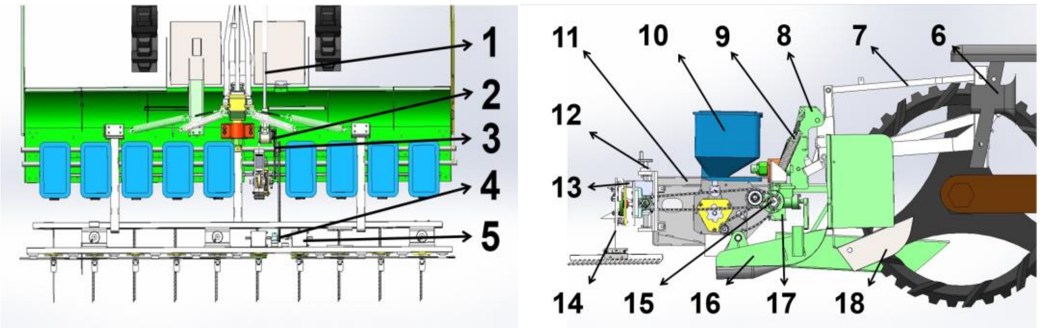


Fig.1 - Structure diagram of the synchronous mulching of rice direct seeder
1 - Transmission shaft; 2 - Gear box; 3 - Double row chain wheel; 4 - Driven sprocket; 5 - Bevel gearbox; 6 - Power chassis of high speed seedling transplanter; 7 - Hydraulic power lift; 8 - Hookup mechanism; 9 -Horizontal profiling mechanism; 10 -Metering device; 11 - Mounting rack; 12 - Slides; 13 - Horizontal mounting rack; 14 - Swing type synchronous mulching equipment; 15 - Transmission system; 16 - Ditching and ridging device 17 - Main horizontal beam; 18 - Profiling mechanism;

The placement of mulching equipment was adjusted to keep 10 mm between the soil surfaces, and the seeder was preceded by ditching and ridging device to open the water furrow and seed furrow. At the same time, the transmission system would support the power to the metering device and the swing synchronous mulching equipment. The mulching plate would break the ridge of the seed furrow to mulch the seeds, and then the direct seeder can sow and mulch at all once.

Build EDEM simulation model

The studies showed the soil diameter was less than 2 mm before seeding in the Poyang Lake region (*Zhu et al., 2020*). To study the interaction between the mulching plate and soil, the discrete element method was introduced to build the simulation model, shown in Fig. 2 (*Peng et al., 2023*). The high moisture of soil model used Hertz-Mindlin simulation model with JKR, and simulation parameters were shown as Table1 *(Zhu et al., 2020; Deng et al., 2022)*. To calculate the soil movement 20-30 mm below the surface in the seed furrow, two soil layers of different colors were established, that is, a 20 mm deep gray surface layer and a 40 mm deep red subsoil layer *(Zhang et al., 2022)*. To promote the accuracy and efficiency of the simulation (*Liu et al., 2021*), the particle size of the topsoil was 2 mm, and the diameter of the subsoil layer was 5 mm. The rice seed diameter was filled with 2 mm particles.

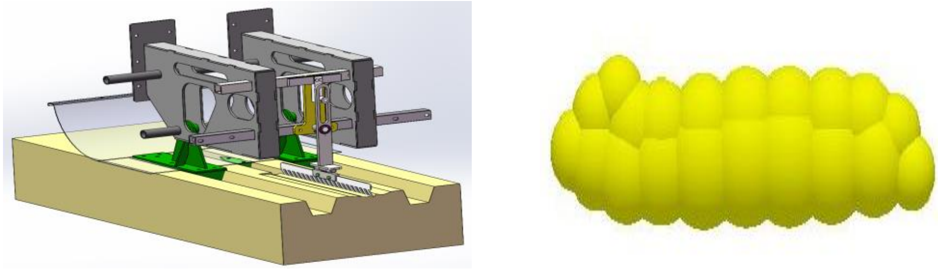


Fig. 2 - Drawings of synchronous mulching equipment and rice seed model in EDEM

Table 1

Parameters of the discrete element simulation model of soil, seed and ABS

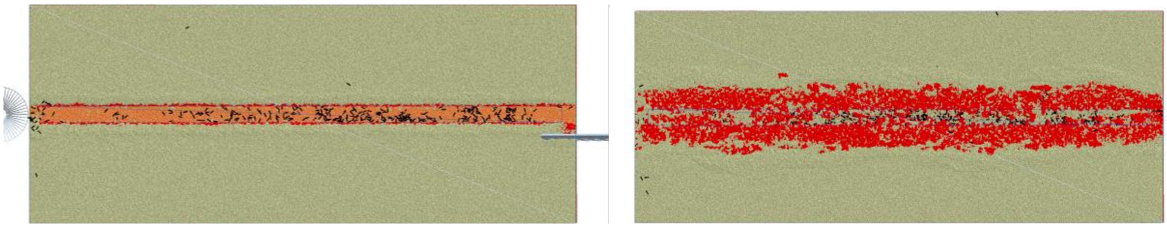
Simulation parameters	Values
Density of ABS, g/cm^3	1.661
Poisson ratio of ABS	0.394
Shear modulus of ABS, Pa	8.9×10^8
Bulk density of soil, g/cm^3	1.650
Poisson ratio of soil	0.308
Shear modulus of soil, Pa	1.2×10^5
Bulk density of rice seed, g/cm^3	0.946
Poisson ratio of rice seed	0.3
Shear modulus of rice seed, Pa	1.08×10^8
Coefficient of static friction between soil and soil	0.3
Coefficient of kinetic friction between soil and soil	0.2
Coefficient of restitution between soil and soil	0.3
Surface energy between soil and soil, J/m^2	1.5
Coefficient of static friction between soil and ABS	0.15
Coefficient of kinetic friction between soil and ABS	0.152
Coefficient of restitution between soil and ABS	0.145
Coefficient of static friction between rice seed and rice seed	0.390
Coefficient of kinetic friction between rice seed and rice seed	0.037
Coefficient of restitution between rice seed and rice seed	0.086
Coefficient of static friction between rice seed and ABS	0.592
Coefficient of kinetic friction between rice seed and ABS	0.001
Coefficient of restitution between rice seed and ABS	0.600
Coefficient of static friction between soil and rice seed	1
Coefficient of kinetic friction between soil and rice seed	1
Coefficient of restitution between soil and rice seed	0.001

The number of soil particles in the surface layer and subsoil layer was respectively 3×10^5 and 5×10^5, and the number of rice seeds was 500. The forward speed and rotating speed were set as before. The simulation time was 3 s, and the length of simulation sample was 1000 mm. The mulching coefficient and mulching depth were used as the evaluation index (*Chen et al., 2021*).

The simulation of synchronous mulching is shown in Fig. 3, and the mulching coefficient is calculated as follows:

$$A_1 = \frac{B_1}{C_1} \text{x} 100\% \tag{1}$$

where A_1 is the mulching coefficient, %; B_1 is the mulching area in the seed furrow, m^2, and C_1 is the total area of the seed furrow, m^2.



(a) Ditching (b) Mulching

Fig. 3 - Sampling diagram of the mulching coefficient

Full factor experiment of the mulching plate

The mulching plate can directly break the ridge and move the soil to the seed furrow, and the seeds are mulched with soil after the direct seeder works. The field conditions would influence the mulching performance of rice stubble, and three different sliding blade structures of the mulching plate were designed with linear function type *(Zhang et al., 2020)*, quadratic function type and exponential function type, as shown in Fig. 4.

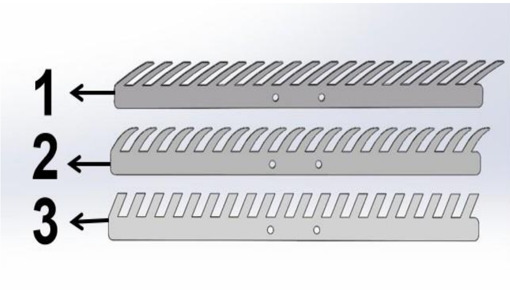


Fig. 4 - Three types of mulching plates

1 - Quadratic function type; 2 - Exponential function type; 3 - Linear function type

To study the performance of mulching plates, rotating speeds and distance of rice stubble were used in a full factor experiment, with a forward speed of 0.8 m/s, and the twisting index and interference of rice stubble were evaluated. The rice stubble is easily twisted by the plate, and the seeds and ridge are also affected by the stubble. Therefore, the twisting index and interference of rice stubble are calculated as Eq. (2) and Eq. (3), as shown in Fig. 5 and Table 2.

(a) 10 cm (b) 30 cm (c) 50 cm

Fig. 5 - Density of rice stubble

Table 2

Full factor experiment

No.	Rotating speed /r·min^{-1}	Mulching plate	Distance of rice stubble/cm
1	70	quadratic function type	10
2	95	exponential function type	30
3	120	linear function type	50

$$D_1=\frac{E_1}{F_1} \tag{2}$$

where:

D_1 is the twisting index, %; E_1 is the twisting number of stubble, and F_1 is the total number of stubble/meter.

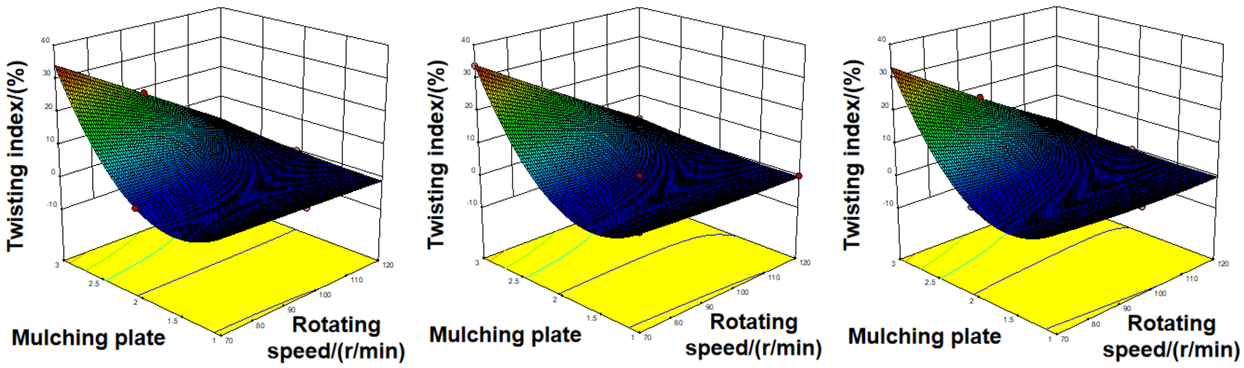
$$G_1=\frac{H_1}{M_1} \tag{3}$$

where: G_1 is the interference index of rice stubble, %; H_1 is the interference length/meter, m, and M_1 is the total length of the seed furrow, m.

RESULTS

Effect of the twisting index and interference index of rice stubble

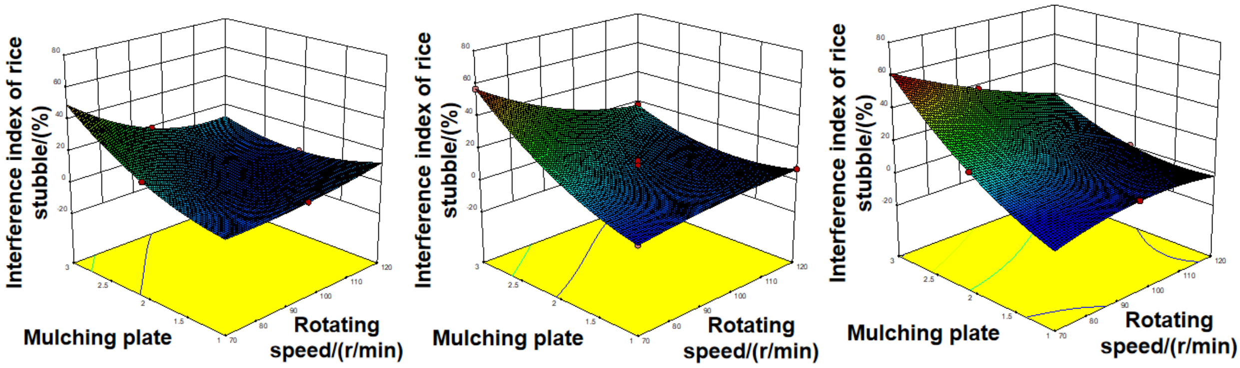
As shown in Fig. 6, when the distance of rice stubble is 10 cm, the rotating speed increases, and the twisting index of the exponential function type mulching plates increases from 0 to 0.98%, and that of linear function type decreases from 32.29% to 3.92%. When the distance increases to 30 cm, the twisting index of the quadratic function type decreases from 2.38% to 0, and that of the linear function type decreases from 23.81% to 4.17%. Once the distance remains at 30 cm, only exponential function type mulching plate has a twisting index, and more rice stubble is left in the field. Therefore, the exponential function type mulching plate has optimal structure for preventing twisting.



Distance of rice stubble: 10 cm *Distance of rice stubble: 30 cm* *Distance of rice stubble: 50 cm*

Fig. 6- Response surface diagram of the twisting index

The interference index of rice stubble is shown in Fig. 7. When the distance of rice stubble is 10 cm, the lower the rotating speed, the greater the interference index, especially for the exponential function type mulching plate with a rotating speed of 95 $r\cdot min^{-1}$ and 20.84%. When the distance increases to 30 cm, the exponential function type and linear function type respectively decrease to 10.42% and 17.92%, with the rotating speed increasing from 70 to 120 $r\cdot min^{-1}$. When the distance of rice stubble reaches 50 cm, these three mulching plates decrease, and the minimum value of the exponential function type is 1.43%. It is smaller than 3.12% and 21.84% respectively compared to the quadratic function type and the linear function type. Therefore, the exponential function type mulching plate is an optimal structure for interference.



Distance of rice stubble: 10 cm *Distance of rice stubble: 30 cm* *Distance of rice stubble: 50 cm*

Fig. 7- Response surface diagram of the interference index of rice stubble

The results indicate that the optimized structure of mulching plates could reduce the twisting index and interference index of rice stubble. The higher the rotating speed, the lower the twisting index and the interference.

Regression analysis

To find the influence relationship of the swing synchronous mulching direct seeder, the mathematical models of regression analysis in the twisting index and interference index are analyzed, shown as Table 3 and Table 4.

Table 3

Variance analysis of the twisting index regression model

Source of variance	III sum of square	Degree of freedom	Mean square	F	p	Significance
Modify model	1469.63	11	133.6	1419.94	< 0.0001	**
Rotating speed/r·min^{-1}	0	1	0	0	1	
Covering plate	604.82	1	604.82	6428.15	< 0.0001	**
Distance of stubble/cm	0.77	1	0.77	8.14	0.0357	*
Rotating speed*Covering plate	210.98	1	210.98	2242.27	< 0.0001	**
Rotating speed*Distance of stubble	0	1	0	0	1	
Covering plate*Distance of stubble	0.77	1	0.77	8.14	0.0357	*
Rotating speed*Rotating speed	0.52	1	0.52	5.56	0.0649	
Covering plate*Covering plate	363.39	1	363.39	3862.11	< 0.0001	**
Distance of stubble*Distance of stubble	0.52	1	0.52	5.56	0.0649	
Rotating speed*Covering plate*Covering plate	0.38	1	0.38	4.07	0.0997	
Residual	142.89	1	142.89	1518.65	< 0.0001	**
Lack of Fit	0.47	5	0.094			
Pure Error	0.47	1	0.47			
Cor Total	0	4	0			
Cor Total	1470.1	16				

Note: *indicates significance, i.e. (p<0.05); **indicates extreme significance, i.e. (p<0.001).

Table 3 shows that the regression model of the twisting index of mulching plate is significant (p<0.0001), mulching plate structure, the interaction between the rotating speed and the mulching plate structure, the interaction between mulching plate structures have significant influence. The stubble distance, the interaction between the mulching plate structure and stubble distance also has significant influence. In this way, the regression mathematical model Y_1 is established as (3), and the determination coefficient R^2 is 0.99.

$$Y_1 = 87.22 - 128.69B_2 + 0.39C_2 + 1.06A_2B_2 - 0.02B_2C_2 + 41.41B_2^{\ 2} + 0.35*10^{-4}A_2^{\ 2}C_2 \quad (4)$$

where: Y_1 is the twisting index, %; A_2 is rotating speed, r/min^{-1}, B_2 is the structure of mulching plate, and C_2 is the distance of stubble, cm.

Table 4

Variance analysis of the interference index in the regression model of rice stubble

Source of variance	III sum of square	Degree of freedom	Mean square	F	p	Significance
Modify model	3337.42	11	303.4	77.42	< 0.0001	**
Rotating speed/r·min^{-1}	516.65	1	516.65	131.84	< 0.0001	**
Covering plate	604.67	1	604.67	154.3	< 0.0001	**
Distance of stubble/cm	53.14	1	53.14	13.56	0.0143	*
Rotating speed*Covering plate	537.54	1	537.54	137.17	< 0.0001	**
Rotating speed*Distance of stubble	3.53	1	3.53	0.9	0.3859	
Covering plate*Distance of stubble	131.33	1	131.33	33.51	0.0022	*
Rotating speed*Rotating speed	31.2	1	31.2	7.96	0.037	*
Covering plate*Covering plate	300.8	1	300.8	76.76	0.0003	**
Distance of stubble*Distance of stubble	7.91	1	7.91	2.02	0.2148	
Rotating speed*Rotating	42.55	1	42.55	10.86	0.0216	*

Source of variance	III sum of square	Degree of freedom	Mean square	F	p	Significance
speed*Covering plate						
Rotating speed*Covering plate*Covering plate	36.47	1	36.47	9.31	0.0284	*
Residual	19.59	5	3.92			
Lack of Fit	0.063	1	0.063	0.013	0.915	not significant
Pure Error	19.53	4	4.88			
Cor Total	3357.02	16				

Note: *indicates significance, i.e. ($p<0.05$); **indicates extreme significance, i.e. ($p<0.001$).

Table 4 shows that the interference index of the regression model for rice stubble with mulching plate is significant ($p<0.0001$). The rotating speed, and the mulching plate structure, the interaction between the rotating speed and the mulching plate structure, the interaction between the mulching plate structures have significant influence. The stubble distance, the interaction between the mulching plate structure and the stubble distance, the interaction between the rotating speeds, the interaction between the square of rotating speed and the structure of mulching plates, the interaction between the rotating speed and the square of rotating speed are significant. Therefore, the regression mathematical model Y_2 is established as (4), and the determination coefficient R^2 is 0.99.

$$Y_2 = -37.10 + 0.69A_2 + 80.55B_2 - 3.09C_2 - 1.87A_2B_2 + 0.29B_2C_2 - 0.16*10^{-3}A_2^{\ 2} + 8.45B_2^{\ 2} + 0.74*10^{-2}A_2^{\ 2}C_2 - 0.34*10^{-3}B_2^{\ 2}C_2 \quad (5)$$

where Y_2 is the interference index, %; A_2 is the rotating speed, r·min^{-1}; B_2 is the structure of mulching plate, and C_2 is the distance of stubble, cm.

The optimal parameters for exponential function type mulching plate are a rotating speed of 120 r·min^{-1} and a disturbance of 50 cm.

Field experiment

To verify the performance of swing synchronous mulching equipment, the field experiment was conducted, and the field soil was operated with rotating tillage. The water moisture of soil was tested with 32% (DH-190 Automatic Halogen Moisture Analyzer, Shanghai Jiashi Electronics Co., Ltd.), and the bulk density of soil was 1.65 g/cm^3 (Nanjing Soil Instrument Factory). The parameters are the same as the simulation model, with 5-6 rice seeds in each hole, and the mulching coefficient and mulching depth are sampled and tested as shown in Fig. 8. The results are shown in Table 5.

Fig. 8 - Field experimental of synchronous mulching

Table 5

Experiment and simulation results

Forward speed/m·s^{-1}	Rotating speed/r·min^{-1}	mulching coefficient/%		Error	mulching depth/mm		Error
		Simulation value	Experiment value		Simulation value	Experiment value	
0.6	90	93.10	87.37	6.15	6.07	5.56	8.40
0.8	120	93.40	98.54	5.50	6.27	5.08	8.98
1.0	150	94.18	91.67	2.67	6.21	5.84	5.96

The rotating speed matched the forward speed of the seeder. When the forward speed was 0.6 m/s, the rotating speed was 90 r·min^{-1}, and when the mulching coefficient was 87.37%, the mulching depth was 5.56 mm.

When the forward speed increased to 0.8 m/s, the mulching coefficient and mulching depth decreased to 98.54% and 5.08 mm respectively; when the forward speed was 1.0 m/s, the mulching coefficient was 91.67%, and the mulching depth was 5.84 mm. The errors between experimental value and simulation value were 2.67- 6.15% and 5.96 -18.98%, respectively. However, the mulching coefficient can reach more than 87.37%, and the simulation values also have significant values. Although there is a significant error in the mulching depth, the value is in the range of 5 -10 mm, which is consistent with previous study.

CONCLUSIONS

(1) To meet the agronomic requirements of rice direct seeding, a swinging synchronous mulching of rice direct seeding machine was designed, with a coverage depth of 5-10 mm.

(2) Three different sliding blades of mulching plate with linear function type, quadratic function type and exponential function type were designed. The bench superconductive with the rotating speed and the stubble distance as the independence, and the twisting index and interference index of rice stubble were used as dependence. The results showed that the structure of the exponential function type mulching plate was optimal.

(3) To study the interaction between mulching equipment and soil, the EDEM simulation model was established by introducing the discrete element method, and its performance was verified by field experiments. The results showed that the synchronous mulching seeder had a rotating speed of 90-150 r·min^{-1} and a forward speed of 0.6 -1.0 m·s^{-1}. The mulching coefficient was 87.37-98.54% and the mulching depth was 5.08 -5.84 mm and the errors are between 2.67~6.15% and 5.96~18.98% respectively compared with the simulation model.

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