HARVEST LOSS TEST AND OPTIMISATION OF KEY COMPONENTS OF OILSEED RAPE CUTTING TABLES
/
油菜割台关键部件收获损失试验与优化

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ABSTRACT
Aiming at the problem of high loss of oilseed rape combine harvesting cutting platform, this paper combines the biological characteristics of oilseed rape, analyses the way and reason of oilseed rape loss, selects the harvester's forward speed, transverse cutter cutting height and longitudinal cutter cutting speed three factors to influence the loss rate of the cutting platform to carry out the study on the significance of the order of significance of the following: cutting speed ＞ forward speed ＞ cutting height. Through the response surface analysis method, the interaction between the factors was obtained. Through the regression model of the factors affecting the loss rate, the parameter optimisation was carried out with the objective of the lowest loss rate, and the optimal parameter combinations being obtained as follows: the forward speed was 5 km/h, the cutting speed was 1.5 m/s, and the cutting height was 50 cm. Finally, the results of the model were obtained to be reliable through the experimental validation.

摘要
针对油菜联合收获割台损失高的问题，本文结合油菜生物特性，对油菜产生损失的方式和原因进行分析，选择收获机前进速度、横向切割器切割高度和纵向切割器切割速度三项因素对割台损失率进行影响显著性研究，其显著性顺序为：切割速度>前进速度>切割高度；通过响应面分析法得到各因素之间两两存在交互作用；通过损失率影响因素回归模型，以损失率最低为目标进行参数优化，求得最优参数组合为：前进速度为 5km/h，切割速度为 1.5m/s，切割高度为 50cm；最后，经试验验证得到模型结果可靠。

INTRODUCTION
Rapeseed is the main oilseed crop in China, and its planting area and output are among the top in the world, which has an important position in China's agricultural production. In the rapid development of agricultural mechanisation today, compared with rice, wheat, corn and other bulk crops, rapeseed in all aspects of ploughing, planting, management, harvesting, breeding of fine varieties still has more room for development. In terms of biological control of oilseed rape, some scholars have experimented intercropping oilseed rape with wheat and intercropping with alfalfa to explore the attractiveness of natural enemies of aphids and the effect of biological control and crop yield (*Hatt et al., 2019; Tajmiri et al., 2017*); in terms of ploughing management, it is important to explore the effects of different ploughing methods on the growth of oilseed rape and its yield, and to combine the oilseed rape agronomic techniques to achieve the optimal management of oilseed rape (*Jankowski et al., 2023; Kristó et al., 2021; Bečka et al., 2021*). In addition, fertiliser application method (*Miersch et al., 2016*), planting density (*Khan et al., 2018; Zhang et al., 2017*), variety and sowing date (*Zorzenoni et al., 2019; Crnobarac et al., 2015*) have also become the focus of research on the full growth cycle of oilseed rape. In terms of mechanised harvesting of oilseed rape, the high rate of seed loss is an important reason restricting its development at present, the average loss rate of oilseed rape combined harvesting reaches 8.54%, and the loss of seed mainly originates from the disturbance of the cutting platform and separation and cleaning and other subsequent work processes, of which the loss generated by the cutting platform accounts for more than half of the total loss (*Wei, 2021; Kendall et al., 2017*). This leads to not only high harvest losses in the development of oilseed rape, but also environmental impacts that cannot be ignored.

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Firstly, the special biological nature of oilseed rape is an important reason for its high harvest losses. During the harvesting period, oilseed rape plants are tall, with many branches and inconsistent growth heights, and the upper part of the angiosperms are intertwined with each other, making it difficult to divide the harvest (*Yiren, 2021*). The lower part of the stalks are thick and tough, the lateral cutter will have impact on the stalks during operation, resulting in the upper part of the angular fruit being subjected to mutual extrusion pressure, and the current widely planted oilseed rape varieties with poor resistance to cracking angle, by vibration, beat, extrusion and other interferences are very easy to blow pods, resulting in oilseed rape drop grain loss; wrapped in the angular fruit, with the colour of the rapeseed being close to the colour of the soil, it is difficult to distinguish and pick up those fallen on the soil (*Yang, 2020; Wu and Wu, 2018; Zhang et al., 2021*). In addition, the low degree of agro-mechanical and agronomic adaptation is also a key cause of oilseed rape losses. At present, most of the cutting platforms used for harvesting oilseed rape are improved on the basis of rice and wheat cutting platforms by lengthening the cutting platforms, adding longitudinal cutters, and adjusting the working parameters and positions of the paddle wheels, and there are no special cutting platforms for oilseed rape. Researchers and scholars at home and abroad select and cultivate excellent varieties of oilseed rape, and at the same time explore the structural parameters and working parameters of each component of the cutting platform and the working parameter relationship between the components (*Fríd et al., 2017*), with a view to taking measures to reduce the harvesting losses of oilseed rape from two important aspects of agro-mechanics and agronomy.

MATERIALS AND METHODS

Analysis of the main working parts of the cutting table

Harvesting Paddle Wheel

The paddle wheel is one of the most common paddles, mainly composed of paddle wheel and paddle bullet teeth, its function is to paddle the oilseed rape to be cut to the cutting platform, support the crop crooked stalks, so that the oilseed rape to achieve the state of easy cutting. Its structure sketch is shown in Fig.1.

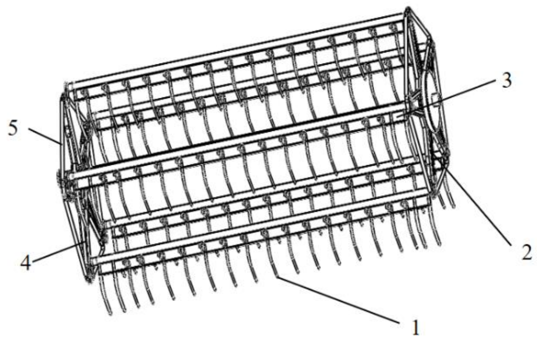

Fig. 1 - Sketch of the structure of the paddle wheel

1 - Bullet teeth; 2 - Eccentric wheel; 3 - Wheel axle; 4 – Spokes; 5 - Tension bar

The motion of the paddle wheel consists of the forward speed of the harvester and the rotary motion of the paddle wheel itself, the trajectory of which is shown in Fig.2.

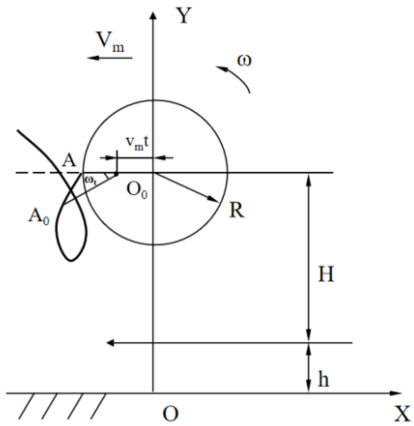

Fig. 2 - Movement trajectory of the plucking wheel

The motion trajectory equation is shown in Equation (1), and in order to ensure that the paddle wheel can play the role of paddle, the necessary condition is the ratio of the circumferential speed V_b of the paddle wheel and the forward speed V_m of the harvester, i.e., the paddle speed ratio $\lambda>1$, so that the motion trajectory of the paddle wheel as a co-cycloid (*Xiao et al., 2020*).

$$\begin{cases} x = V_m t + R\cos\omega t \\ y = H - R\sin\omega t + h \end{cases} \tag{1}$$

where:

V_m - Harvester forward speed, [m/s]; t - rasp wheel working time, [s]; R - radius of the paddle wheel, [m]; ω - Angular speed of rotation of the paddle wheel, [rad/s]; H - Vertical distance between the centre axis of the paddle wheel and the main cutter, [m]; h - height of the main cutter above ground, [m]

Through a large number of experimental studies by scholars at home and abroad, it is indicated that in the optimisation of the structure of the paddlewheel, the selection of eccentric paddlewheel, paddlewheel flexible elastic teeth, and elastic teeth into the harvesting method of slanting insertion is most suitable for the harvesting of oilseed rape because the growth of oilseed rape angular fruits is disordered and seriously entangled with each other, and the method of slanting insertion of harvesting is better adapted to the biological characteristics of oilseed rape, and it is able to reduce the loss of falling grains caused by insertion of elastic teeth into the inner part of the angular fruits (*Zhou et al., 2023*). In the optimisation of the working parameters of the paddlewheel, most of the scholars carried out optimisation tests in terms of the paddlewheel speed ratio, the horizontal position of the paddlewheel relative to the cutter, the vertical position of the paddlewheel and the paddlewheel rotational speed, and the optimisation of the parameters was carried out with the objective of reducing the loss rate.

Cutter

As one of the key components of the cutting platform, the cutting effect of the cutter has an important impact on the harvesting quality of the harvester. At present, the cutter used in oilseed rape harvester is reciprocating cutter, which mainly consists of reciprocating cutter and fixed support part, and its structure sketch is shown in Fig. 3.

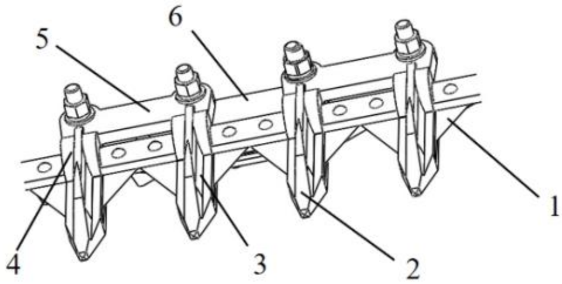

Fig. 3 - Schematic diagram of the structure of the reciprocating cutter

1 - Dynamic blade; 2 - Fixed blade; 3 – Presser; 4 – Shield; 5 - Shield beam; 6 - Tool holder

The working principle of the reciprocating cutter is that when the knife bar makes reciprocating movement, the moving blade and the fixed blade form a shear, which cuts off the oilseed rape stalks (*Wu Shouyi, 1992*). At present, the reciprocating cutter is mainly divided into three types: standard type, low cutting type and double knife pitch stroke type, the main difference is the relationship between the linear motion stroke s of the moving blade and the installation spacing t between the adjacent moving blade and the installation spacing t_0 between the adjacent fixed blade.

The structural dimension relationship of the standard reciprocating cutter is $s=t=t_0=76.2$ mm. This type of cutter has a faster cutting speed, is more adaptable to crop stalks, and is the most widely used cutter at present. Its structural shape is shown in Fig.4. Low-cutting type reciprocating cutter structure size for $s=t=2t_0=76.2$ mm, due to the two fixed blades between the fixed blade and a fixed blade, blade spacing is small, the crop stalks of the transverse skew amount is small, the cut stubble is lower, but prone to plugging the knife phenomenon. The structural dimension relationship of the double blade spacing stroke type reciprocating cutter is $s=2t=2t_0=152.4$ mm, which is characterized by lower cutting speed and small inertia force, but the cutting load on the cutting edge of the cutter is not uniform.

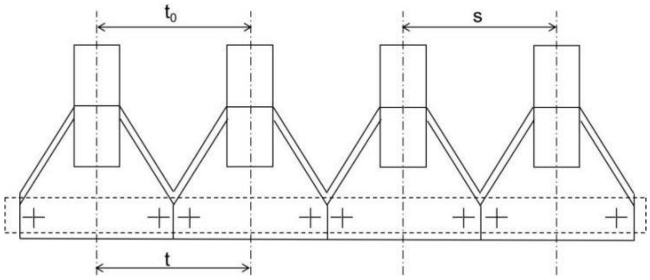

Fig. 4 - Standard Type II reciprocating cutter

Due to the serious entanglement and difficulty in dividing the upper end of the rape horn, the use of ordinary branching devices has a pulling force on the rape horn, resulting in the loss of thin and crispy horn pods and grains drop. The oilseed rape cutting table therefore needs to be fitted with a transverse cutter, which cuts the stalks, and a longitudinal cutter, which cuts the oilseed rape cuticle and acts as a branch. In the optimisation of the cutter structure, the main research is on the cutting mode of the cutter, the selection of the three types as well as the shape, number and angle of the blades; in the optimisation of the cutter's working parameters, the main optimisation is on the cutting height of the transversal and longitudinal cutters, the cutting speed and its ratio to the forward speed of the harvester (cutting speed ratio).

Field trials

Test device and conditions

The experiment was carried out in the experimental field of Weiyuan Town, Mutual Aid County, Haidong City, Qinghai Province, the experimental oil-seed rape variety is "Qingyou 331", the test oil-seed rape has already reached the optimal harvesting period, and the specific parameters are shown in Table 1.

Table 1

Test rapeseed parameters

Parametric	Unit (of measure)	Numerical value
Plant height	cm	163~178
Branching height	cm	45~58
Thousand-grain weight	g	4.0
Capacity	g/L	685
Seed moisture content	%	12
Stalk moisture content	%	17
Mean cuticle diameter	cm	33
Average cuticle thickness	cm	62

The harvester used for the test was a Dongfeng 4LZ-5.2AJ(G4) full-feed combine harvester, with the specific parameters shown in Table 2, and the other test supplies were electronic scales and catch tanks.

Table 2

Dongfeng 4LZ-5.2AJ(G4) fully fed combine harvester parameters

Sports event	Unit (of measure)	4LZ-5.2AJ(G4)
Overall dimensions (L*W*H)	mm	5100*2530*2850
Motive force	kW	92
Overall quality	kg	3730
Cutting table working width	mm	2200

Sports event	Unit (of measure)	4LZ-5.2AJ(G4)
Minimum Ground Clearance	mm	315
Feed rate	kg/s	5.2
Efficiency of production	hm^2 /h	0.35~0.75
Cutter type	/	Standard II
Wheel type	/	Toothed

Test scheme and loss rate measurement method

Regional division of test fields

The cutting width of the harvester is 2.2 m, so the width of the test area is selected to be 3 m, and the length of the test area is 25 m, of which, the per-harvesting stage is 5 m, the test harvesting stage is 20 m, the 20 m test area is divided into the normal harvesting area and the actual loss rate measurement area, and the test is finished when the cutter reaches the end of the test area at the position of 25 m, and the position of 4.5 m away from the end of the test is selected to be the lot for the measurement of actual loss rate of the cutter. The distribution map of the test field is shown in Fig. 5.

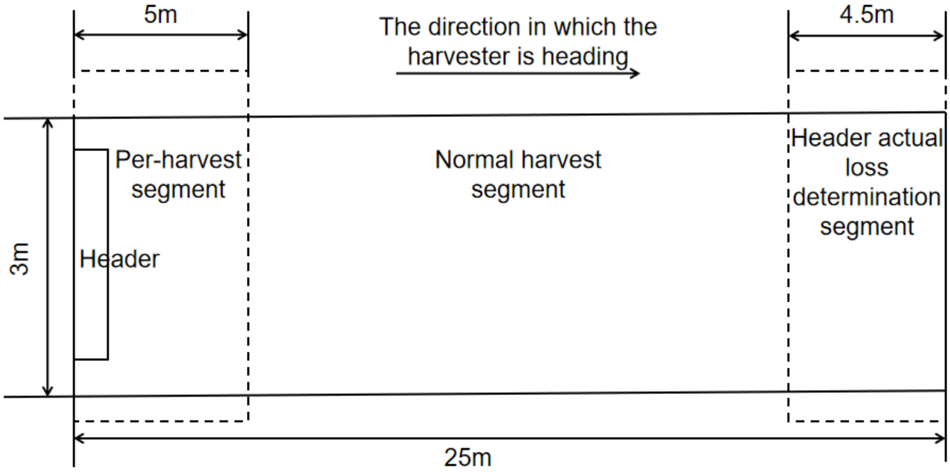

Fig. 5 - Distribution Map of Experimental Field Area

By analysing the biological characteristics of oilseed rape, the working principle and movement trajectory of the key components such as the paddle wheel and the cutter, combined with the review and summary of a large number of literature and books and other information, the cutting height of the transverse cutter, the longitudinal cutter's cutting speed and the forward speed of the harvester were selected as three factors to select five levels for the single-factor test, and the adjustment ranges of the test factor's working parameters are shown in Table 2.3. Among them, the cutting height of the transverse cutter was realized by adjusting the height of the cutting table. The results of the single-factor test were analysed and summarized, and the better three levels of each factor were selected for the orthogonal test to analyse the significance of the effect of each factor on the loss rate of the cutting table, explore the interaction between the factors through the response surface analysis method, and obtain the regression model of the factors and the loss rate of the cutting table, and obtain the optimal parameter combination with the lowest loss rate of the cutting table as the goal.

Table 3

Range of operating parameters of test factors

Parametric	Unit (of measure)	Adjustment range
Harvester forward speed	km/h	3~7
Cross cutter cutting height	cm	40~60
Longitudinal cutter cutting speed	m/s	1~2

Loss rate measurement method

According to the agricultural machinery promotion appraisal syllabus "oilseed rape combine harvester" (DG/T057), the test loss rate determination method is as follows: before the test to make three 2.5 m × 0.1 m × 0.06 m thin steel plate receiving sample groove, groove padded with flannel. In the measurement area, take three measurement points at equal spacing, choose the appropriate oilseed rape plant spacing at each measurement point, vertical operation direction across the width of the prototype operation to eradicate the corresponding flat-bottomed grooves with the sampling groove, and the sampling groove lying in which the groove is flush with the ground (*MOA, 2006; SAC, 2008*). When placing the sampling groove, one end of the sampling groove should be flush with the uncut rape end, and the other end, which exceeds the cutting width of the prototype, should be placed on the side of the vertical side cutter, to ensure that it can pick up the loss of rapeseed grain splash caused by the side vertical cutter, and the specific distribution is shown in Fig. 6.

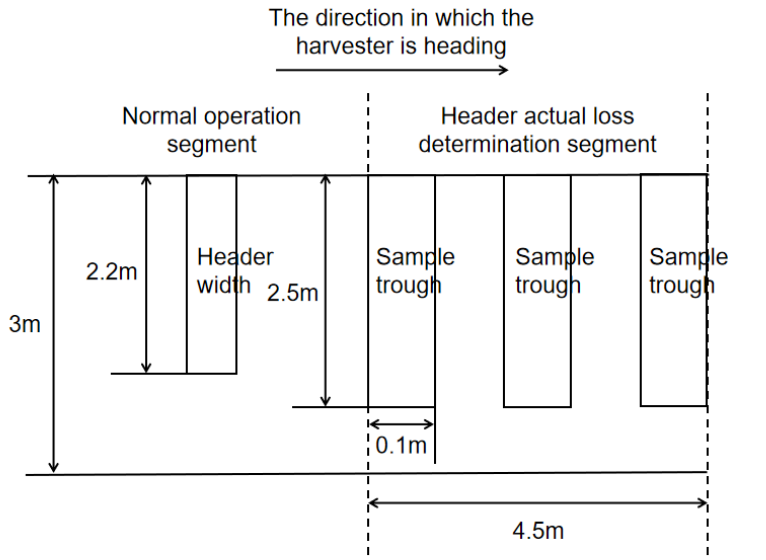

Fig. 6 - Sample slot distribution diagram

The loss rate of cuttings is calculated as shown in Equation (2). That is, the ratio of the actual loss of the cutting table in the measurement area to the total weight of the grains in the reception area is expressed as a percentage.

$$S = \frac{W(B \times L)}{M} \times 100\% \tag{2}$$

where:

S - Cutting table loss rate, [%];

W - Actual losses per square meter of the cutting table, [g];

B - Average actual cutting width, [m];

L - Length of the measurement area, [m];

M - Total weight of seeds caught in the catchment area, [g]

RESULTS

Analysis of single-factor test results

The effect of forward speed on the header loss rate

Test conditions: to ensure that the other components of the harvester working parameters remain unchanged, the forward speed is increased from 3 km/h to 7 km/h, and the change in the loss rate of the cutting deck is shown in Fig. 7. As can be seen from the figure, in the case of other factors remaining unchanged, the loss rate of the cutting platform with the increase in forward speed shows a trend of first decrease and then increase, and the magnitude of the change is larger, the loss rate is the lowest in the forward speed of 5 km/h, which can be shown that the forward speed of the cutter has a greater impact on the loss rate of the cutting platform. Forward speed is too slow, the paddle wheel will repeatedly slap the rape horn fruit, forward speed is too fast, the cutter cutting is not timely, the horn fruit leakage phenomenon appears, and the vibration frequency is accelerated. Therefore, too fast or too slow forward speed will increase the harvest loss.

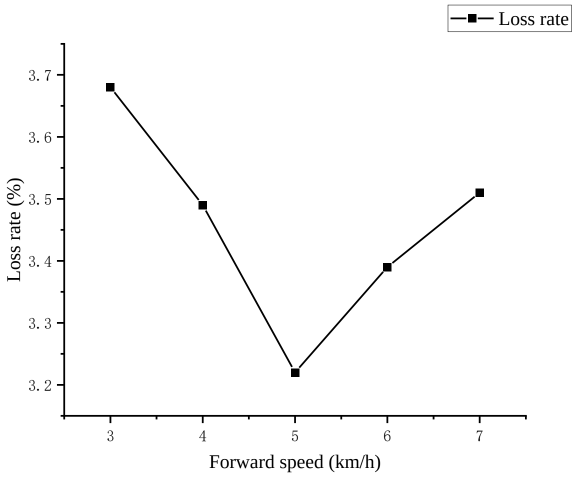

Fig. 7 - Forward velocity single-factor test results

Effect of cutting speed on header loss rate

Test conditions: to ensure that the other components of the harvester working parameters remain unchanged, the cutting speed is increased from 0.9 m/s to 2.1 m/s, and the change in the loss rate of the cutting platform is shown in Fig. 8. As can be seen from the figure, in other factors work parameters remain unchanged, gradually increase the cutting speed of the vertical cutter knife, the cutter loss is the first to decrease and then increase, when the cutting speed is 1.5 m/s, the lowest loss rate of the cutter is 3.22%. The curve changes in the image show that the cutting speed has a significant impact on the cutter loss rate. The reason is that the cutting speed is too low, and the forward speed of the harvester is not enough to match when the harvester is moving forward, the cutter is too late to cut, and the resulting vibration and angular fruit perturbation increases, increasing the loss of the cutting platform; when the cutting speed is too fast, the vibration frequency accelerates, and there is a repeated cutting phenomenon, so the seed splash is serious.

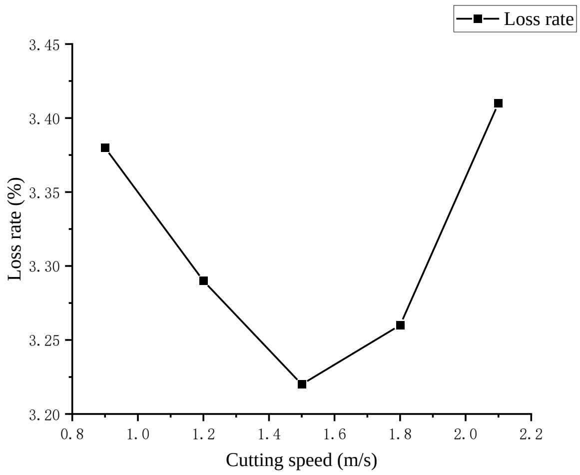

Fig. 8 - Single factor test results of cutting speed

Effect of cutting height on header loss rate

Test conditions: ensure that the working parameters of other parts of the harvester remain unchanged, the cutting height is increased from 40cm to 60cm, and the change of the loss rate of the header is shown in Fig. 9. As can be seen from the figure, when the working parameters of other factors remain unchanged, the cutting height is adjusted, and when the cutting height is 50 cm, the loss rate of the header is the lowest. When the cutting height is between 40 to 50 cm, the loss rate changes very little. When the cutting height is higher than 50cm, the loss rate of oilseed rape header shows a significant increase trend, indicating that the cutter is gradually close to the centre of the rapeseed horn and fruit layer, and the number of rapeseed stalks cut by the cutter decreases and the number of rape pods increases, which will definitely cause the loss of grain drop.

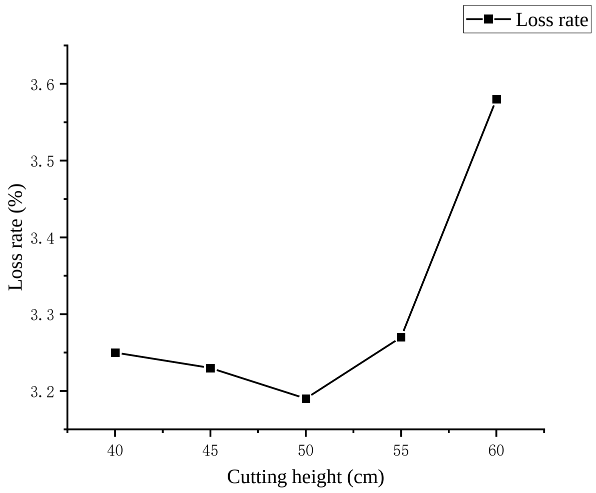

Fig. 9 - Single factor test results of cutting height

Analysis of multivariate test results

To further investigate the order of significance of each factor effect on the loss rate of the cutting table and the interaction between the factors, a three-factor, three-level quadratic regression orthogonal test was conducted on the influencing factors, and the levels of the relevant factors are shown in Table 4, and the results of the test are shown in Table 5.

Table 4

Encoding Table of Factors for Header Loss Rate Test Level

Level (of achievement etc.)	Considerations		
	Forward speed/(km/h)	Cutting speed/(m/s)	Cutting height/(cm)
	x_1	x_2	x_3
-1	4	1.2	45
0	5	1.5	50
1	6	1.8	55

Table 5

Results of Header Loss Rate Test

Test No.	Experimental factors			
	Forward speed / (km/h)	Cutting speed / (m/s)	Cutting height / (cm)	Cutting table loss rate / (%)
	x_1	x_2	x_3	y
1	-1	-1	0	3.45
2	1	-1	0	3.47
3	-1	1	0	3.52
4	1	1	0	3.55
5	-1	0	-1	3.32
6	1	0	-1	3.35
7	-1	0	1	3.31
8	1	0	1	3.41
9	0	-1	-1	3.27
10	0	1	-1	3.48
11	0	-1	1	3.46
12	0	1	1	3.41
13	0	0	0	3.15
14	0	0	0	3.13
15	0	0	0	3.14
16	0	0	0	3.09
17	0	0	0	3.11

The interaction of factors affecting the loss rate of the cutter was analysed with the help of response surface analysis and the regression equation was obtained using ANOVA and the results are shown in Table 6.

Table 6

Analysis of variance result

Source	SS	DF	MS	F-value	p-value
Modelling	0.39	9	0.043	80.16	<0.0001
x_1	0.00405	1	0.00405	7.57	0.0284
x_2	0.012	1	0.012	22.45	0.0021
x_3	0.003612	1	0.003612	6.75	0.0355
x_1x_2	0.000025	1	0.000025	0.047	0.8350
x_1x_3	0.001225	1	0.001225	2.29	0.1740
x_2x_3	0.017	1	0.017	31.59	0.0008
${x_1}^2$	0.11	1	0.11	196.47	<0.0001
${x_2}^2$	0.20	1	0.20	365.49	<0.0001
${x_3}^2$	0.018	1	0.018	33.76	0.0007
Residual	0.003745	7	0.000535		
Lost proposal	0.001425	3	0.000475	0.82	0.5472
Inaccuracies	0.00232	4	0.00058		
Aggregate	0.39	16			

Based on the ANOVA results, the p-value of the model $<$ 0.01 indicates that the model is highly significant and the p-value of the misfit term $>$ 0.05 is not significant, indicating that the model is reliable and well-fitted. The p-value of the primary term x_2, interaction term x_2x_3, and secondary terms x_1^2, x_2^2, and x_3^2 is $<$ 0.01 indicating that the effect on cutter loss rate is highly significant, the p-value of the primary terms x_1, x_3< 0.05 indicating that the effect on cutter loss rate is significant and other factors are not significant. Comparing the p-values, the order of significance of the effects can be determined as follows: cutting speed x_2 > forward speed x_1 > cutting height x_3, and after removing the insignificant terms the fitted equation of the loss rate of the cutting table is obtained as follows:

$$y = 3.12 + 0.23x_1 + 0.039x_2 + 0.021x_3 - 0.65x_2x_3 + 0.16{x_1}^2 + 0.22{x_2}^2 + 0.66{x_3}^2 \tag{3}$$

Interaction analysis

The response surface of the effect of each test factor on the cutting table loss rate is shown in Fig.10, when the cutting height is located at the centre level of 50 cm, keeping the cutting speed constant, the loss rate of the cutting table tends to decrease and then increase with the increase of the forward speed; when keeping the forward speed constant, gradually increasing the cutting speed, the loss rate of the cutting table decreases first and then increases.

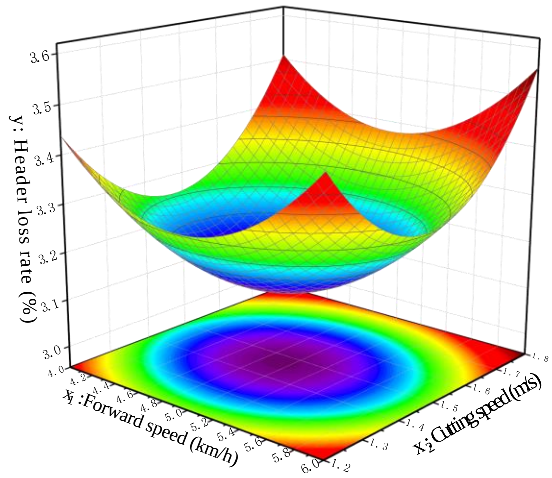

Fig. 10 - Influence of forward speed and cutting speed on the loss rate of the cutting table

From Fig. 11, it can be seen that when the cutting speed is at the centre level of 1.5 m/s, keeping the cutting height unchanged, the loss rate of the cutting table has a tendency to decrease and then increase with the increase of the forward speed, and the magnitude of the change is large; when keeping the forward speed unchanged, the loss rate of the cutting table increases with the increase of the cutting height, and the loss rate decreases and then increases, but the magnitude of the change is relatively small.

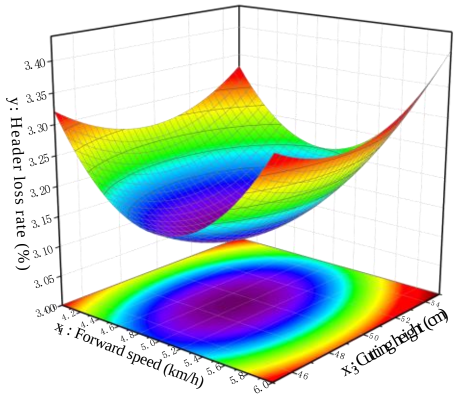

Fig. 11 - Influence of forward speed and cutting height on the loss rate of the cutting table

From Fig. 12, when the forward speed is at the centre level of 5 km/h, keep the cutting height unchanged, the loss rate of the cutting table tends to decrease and then increase with the increase of cutting speed; keep the cutting speed unchanged and gradually increase the cutting height, the loss rate of the cutting table has a small change, and the overall view shows an upward trend.

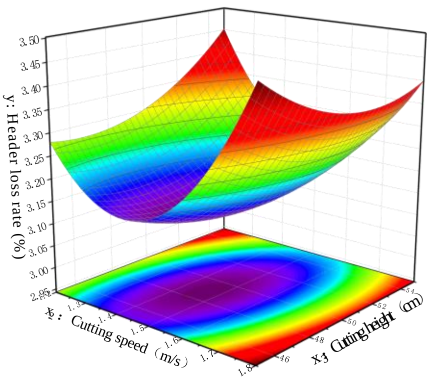

Fig. 12 - Influence of cutting speed and cutting height on the loss rate of the cutting table

CONCLUSIONS

To improve the effect of oil-seed rape harvesting, it is necessary to control the influencing factors in the optimal combination of parameters for harvesting operations, through the single-factor, multi-factor test and the analysis of the interaction between the factors, with the lowest loss rate of the cutting platform as the goal, the regression model in the range of the level of each factor test to optimize the solution, and get the optimal combination of working parameters as follows: the forward speed of 5 km/h, the cutting speed of 1.5 m/s, the cutting height of 50 cm, the loss rate of the cutting platform of 3.12%, the cutting speed ratio of 1.08. To further verify the reliability of the model, three tests were carried out in the experimental field using the above parameter combination results, and the test results are shown in Table 7, which shows that the error between the test results and the optimization results is less than 5%, indicating that the model is reliable.

Table 7

Comparative test results

Parametric	Cutting table loss rate (percent)	Cutting speed ratio
Optimal value	3.12	1.08
Test average	3.17	1.05
Relative error	0.05	0.03

The high gloss of oil-seed rape combined harvesting is an important reason restricting the development of oilseed rape mechanization, and the loss of the cutting platform accounts for a large proportion of the loss of the whole machine, and the investigation of the influence of the key components of the cutting platform on the loss rate is a key step to reduce the loss of oilseed rape harvesting.

The high loss of combined harvest of rapeseed is an important reason restricting the development of rapeseed mechanization. The loss of the header accounts for a large proportion of the loss of the whole machine, so exploring the influence of the key components of the header on the loss rate is a key step to reduce the harvest loss of rapeseed. In this paper, by reviewing a large number of literatures and books, combined with the summary of the biological characteristics of rapeseed, this paper analysed the ways and causes of rapeseed loss. The main forms of loss are grain splash loss, cut miss loss, and rapeseed drop loss due to cracking of rapeseed pods. The main reason is that the thin and brittle nature of rape pods can easily lead to cracking of rape pods, which increases the difficulty of separating crops. In addition, the low degree of agronomic matching of agricultural machinery is also an important reason. The three factors of forward speed, cutting height and cutting speed were selected to study the significant impact on the loss rate of the header, and the interaction between the factors was analysed. By establishing a regression model of the influencing factors of the loss rate, the parameters were optimized with the goal of the lowest loss rate, and the optimal combination of parameters was obtained, and the results of the model were verified by experiments to be reliable.

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