EFFECT OF DITCHING'S PARAMETERS ON OPERATION QUALITY OF ORCHARD DITCHING-FERTILIZER MACHINE
/
开沟参数对果园开沟施肥机作业质量的影响

ChunBao Xu[1)], HongJian Zhang[1)], ShuangXi Liu[1,2)], Chengfu Zhang[4)], Junlin Mu[1)], JinXing Wang[*1,3)]
[1)] College of Mechanical and Electronic Engineering, Shandong Agricultural University, Taian 271018, China;
[2)] Shandong Provincial Key Laboratory of Horticultural Machinery and Equipment, Taian 271018, China;
[3)] Shandong Provincial Engineering Laboratory of Agricultural Equipment Intelligence, Taian 271018, China;
[4)] Gaomi City Yifeng Machinery Co., Ltd., Gaomi 261500, China;
Tel: +86 05388246826; E-mail: jinxingw@163.com
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ABSTRACT
This study aims to evaluate the effects of different parameter settings on the ditching performance using a ditching-fertilizer. We aimed to improve the performance of ditching-fertilizer machine performance in sustainable agriculture. With Box-Behnken experimental design method, taking forward speed, the rotation speed of the ditching cutter, and the deflection angle of ditching cutter as experimental factors, taking ditching depth stability and soil coverage rate as test indexes, the operation parameters of orchard ditching-fertilizer machine are studied. The regression model between test indexes and experimental factors is established, and the influence of each factor on the experimental indexes is analyzed. The test factors are comprehensively optimized. The results show that when the forward speed is 0.8km/h, the rotation speed of the ditching cutter is 348r/min, and the deflection angle of the ditching cutter is 32°, the ditching effect is the best. At this time, the stability coefficient of the ditching depth is 98.33%, and the soil coverage rate is 81.53%. As for the field test, which measured the stability coefficient of ditching depth, and the average soil cover rate is 96.24%, and 79.14%, respectively, and the relative errors from the optimized value are 2.17%, and 3.02%, respectively.

摘要
针对果园开沟作业存在开沟深度稳定性差、覆土率低等问题，基于离散元仿真开展果园开沟施肥机开沟作业参数优化试验，以探究整机作业工况下开沟装置作业参数对开沟深度稳定性、覆土率的影响规律。应用 Box-Behnken 试验设计方法，以前进速度、开沟刀转速、开沟刀偏转角为试验因素，以开沟深度稳定性、覆土率为试验指标，对果园开沟施肥机作业的参数进行试验研究，建立了试验指标与试验因素之间的回归模型，分析了各因素对试验指标的影响，并对试验因素进行了综合优化。结果表明，当前进速度为 0.8km/h、开沟刀转速为 348r/min、开沟刀偏转角为 32°时，开沟深度稳定性达到 98.33%、覆土率达到 81.53%。田间试验实测开沟深度稳定性、覆土率平均值分别为96.24%和79.14%，与优化值相对误差分别为2.17%和3.02%。研究结果可为果园开沟装置的结构改进和开沟作业参数控制提供参考。

INTRODUCTION
China is a big country of fruit production and consumption, which the cultivated area and output of fruit trees rank first in the world *(Huairui Shu et al, 2018; Xiuxin Deng et al, 2018)*. According to the National Bureau of Statistics, the planting area and fruit output of orchards are 11.87493 million hectares and 256.88 million tons respectively. In recent years, the level of orchard production and management mechanization in China is gradually improving. Among them, orchard ditching-fertilizing technology and equipment had made great progress, and gradually became the industry research hotspot *(Xiwen Luo et al, 2016;Zhi Chen, 2001)*. Orchard ditching-fertilizer machines can complete ditching, fertilization, soil covering, and other operational processes at one time *(Yichuan He et al, 2018)*. Comparing with traditional manual ditching fertilization, it has higher efficiency, low cost, and good fertilization effect. However, the complex structure of the orchard ditching-fertilizer machine, the harsh working environment, the different material composition, the large attribute difference, the diversified movement characteristics, and other factors have caused the ditching operation to have poor stability of the ditching depth and low soil cover rate. This directly affects the quality of orchard ditching operations and the yield of fruit trees *(Yao Fan et al, 2013; Yuexiang Lin et al, 2020)*.

As the main working part for the ditching-fertilizer machine, the performance of the ditching device directly affects the quality of the ditching operation. At present, domestic and foreign scholars have carried out relevant research on the structural design and optimization of orchard ditching devices, analysis of soil movement characteristics, influence law of ditching power consumption, etc. *(Dawei Liu et al, 2019; Aili Hasimu et al, 2014; Honglei Jia et al, 2020)*. *Wang Shaowei et al., (2019),* designed the ditching components of the Mountain Orchard ditching machine, optimized the structure parameters of the ditching blade by simulation test, and analyzed the influence of operation parameters on ditching power consumption. *Zhang Yongliang et al., (2012),* applied the theory of throwing soil to analyze the process of throwing soil, finding the trajectory equation of the thrown soil particles, establishing a mechanics model of soil discrete element contact, and studying its throwing performance with the method of experimental verification. *Kang Jianming et al., (2016),* established the finite element model of soil ditching cutter head by using the smoothed particle hydrodynamics method and obtained the variation law of power consumption of the slotting cutter head in the soil cutting process through simulation analysis. *Barr et al., (2016),* studied the effects of different openers on soil disturbance and soil pressure at different speeds through the orthogonal test and reduced soil disturbance by increasing the ditching operation speed. *Abdul et al., (1999),* analyzed the influence law of subsoiling shovel on the sandy soil cutting process and established a regression equation between traction force and soil moisture content and cutting depth.

Based on the above researches, the parameters of orchard ditching operation mainly affect the ditching power consumption, soil throwing performance, soil cutting speed, and then affect the stability of the ditching operation and the soil coverage rate. This paper takes the optimal ditching depth stability and soil cover rate as the research objectives, and uses the ditching device of self-developed orchard ditching-fertilizing to complete the ditching operation parameter optimization test based on the discrete element simulation method. This article explores the influence law of ditching operation parameters on the stability of ditching depth and soil coverage rate.

MATERIALS AND METHODS

Ditching operation parameters analysis

The ditching device is mainly composed of a ditching transmission box, ditching cutter head, and ditching cutter. The operation process is shown in Figure. 1. When working, the power output from the tractor is transmitted to the ditching transmission box, which drives the ditching cutter head and ditching cutter to rotate, to realize the ditching operation. According to the structure and working parameters of the ditching device of the orchard ditching-fertilizer machine, combined with the preliminary test, three key parameters affecting the operation quality were selected in this experiment: forward speed v, rotation speed of ditching cutter n, deflection angle of ditching cutter α.

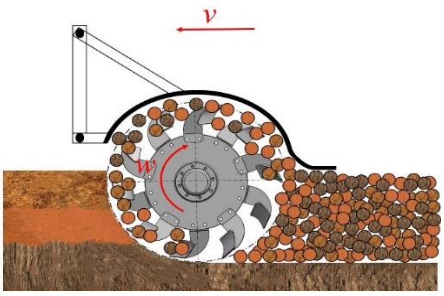
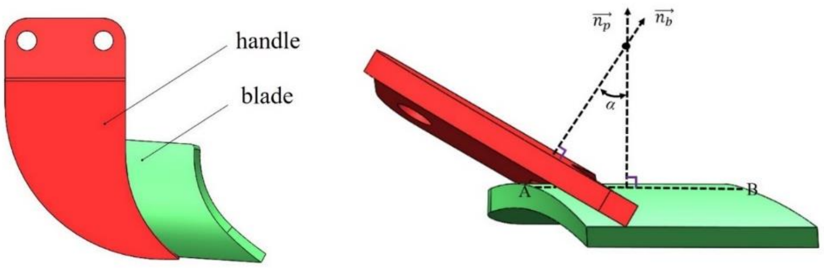


Fig. 1 - Schematic diagram of ditching operation

The forward speed directly affects the performance of the orchard ditching-fertilizer machine *(Xiaopeng Liu et al, 2019)*. According to the actual operation requirements and NY/T740—2003, the forward speed range of orchard ditching-fertilizer machinery is set as 0.8~1.2m/s. The motion parameters of the ditching parts in the ditching device affect the operation performance, especially the rotation speed of the ditching cutter determines the throwing distance, and its size directly affects the power consumption *(Jiqiang Peng et al, 2018)*. According to the previous field test, the best rotation speed range of a ditching cutter is set at 320~450 r/min.

In ditching operation, the ditching cutter should meet the requirements of cutting and throwing soil *(Guangwei Wu et al, 2014)*. According to the actual needs of ditching operation, the concave cutter with good cutting and throwing capacity is selected *(Xu Ma et al, 2001)*.

The concave cutter is mainly composed of a handle and a blade, and the included angle is the deflection angle of the ditching cutter, as shown in Figure. 2. The value of the ditching cutter deflection angle directly affects the operation contour of the ditching device. According to the actual operation requirements, combined with the previous field test, the optimal range of ditching cutter deflection angle is set at 25° to 45°.



(a) (b)

Fig. 2 - Structure and deflection angle of ditching cutter

(a) Structure of the ditching cutter; (b) deflection angle of the ditching cutter

Note: the straight line AB is the intersection line between the blade surface and its tangent plane. $\overrightarrow{n_p}$ is the normal vector perpendicular to the tangent plane; $\overrightarrow{n_b}$ is the normal vector perpendicular to the plane of the handle.

Stability coefficient of ditching depth y_1

The stability degree of the ditching depth of the ditching-fertilizer machine is expressed by the stability coefficient y_1 of the ditching depth under the given working conditions. The calculation formula is as follows.

Through the analysis of the movement of fertilizer particles, we know that three factors affect the fertilizer discharge effect of the orchard double row ditching-fertilizing machine: one is the mechanical structure parameters of the machine; the other is the characteristics of the fertilizer itself; the third is the environmental factors. Under the influence of irresistible environmental factors and the characteristics of fertilizer itself, this study mainly studies the influence of the structural parameters of the machine on the law of fertilizer discharge to solve the problems in practical work.

$$h={\sum_{i=1}^{N} h_i}/{N} \tag{1}$$

$$S=\sqrt{\frac{\sum_{i=1}^{N}(h_i-h)^2}{N-1}} \tag{2}$$

$$V=\frac{S}{h}\times 100\% \tag{3}$$

$$y_1=1-V \tag{4}$$

where h is average ditching depth, cm; h_i is ditching depth of the i^{th} measuring point, cm; N is selected measuring points in the operation area; S is the standard deviation of ditching depth, cm; V is variation coefficient of ditching depth, %; y_1 is stability coefficient of ditching depth, %.

Coverage rate y_2

During the ditching operation, the soil is cut by the cutter and scattered. Under the action of the covering device, most of the soil is rebounded back into the ditching, and some residual splash soil is distributed in a triangle shape outside the ditching. The soil coverage rate is the proportion of soil volume in trapezoidal ditching to the total volume of soil scattered by the ditching cutter.

$$y_2=\frac{\sum_{i=1}^{n}\frac{Q_{1i}}{Q_{0i}}}{n}=\frac{\sum_{i=1}^{n}\frac{S_{1i}L}{(S_{1i}+S_{2i})L}}{n}=\frac{\sum_{i=1}^{n}\frac{S_{1i}}{S_{1i}+S_{2i}}}{n}=\frac{\sum_{i=1}^{n}\frac{N_{1i}}{N_{0i}}}{n} \tag{5}$$

where Q_{1i} is soil volume in the trapezoidal ditch after operation; Q_{0i} refers to the total volume of soil scattered during trenching; S_{1i} refers to the projected area of soil in the trapezoidal ditch after operation; S_{2i} is the projected area of the soil thrown out when ditching; L is forward distance; N_{1i} is the number of soil particles in the trapezoidal ditch after ditching; N_{0i} is the number of soil particles in the trapezoidal ditch before ditching.

Establishment of geometric model of ditching device

To shorten the simulation time, reduce the amount of simulation calculation, and improve the simulation efficiency, the three-dimensional model of the ditching device is reasonably simplified *(Shuai Ma et al, 2018)*. Among them, to ensure the simulation accuracy, the ditching device model is treated with 1:1, and the ditching transmission gear, bearing, support shaft, and other parts that do not directly contact the orchard soil are simplified. Import the processed 3D model into EDEM simulation software, as shown in Figure 3.

Establishment of the ditching soil model

An accurate soil particle model is the basis to ensure the validity of simulation results. Existing studies have shown that the "Hertz Mindlin with JKR" contact model can well simulate the interaction between particles by introducing surface energy *(Xuezhen Wang et al, 2018)*. Therefore, the "Hertz Mindlin with JKR" contact model considering the adhesion force between particles is selected for discrete element simulation.

According to the overall size and operation parameters of the ditching device, a virtual soil bin with a size of 3000mm × 800mm × 400mm was established in EDEM software. To accurately simulate the interaction process between the ditching device and soil, the radius of the soil particle unit is determined to be 8 mm in combination with reference *(Kan Zheng et al, 2016)*. According to the simulation parameters in Table 2, the soil particle model of each layer is generated. Its thickness and section shape is similar to the actual situation in the field, as shown in Figure. 3.

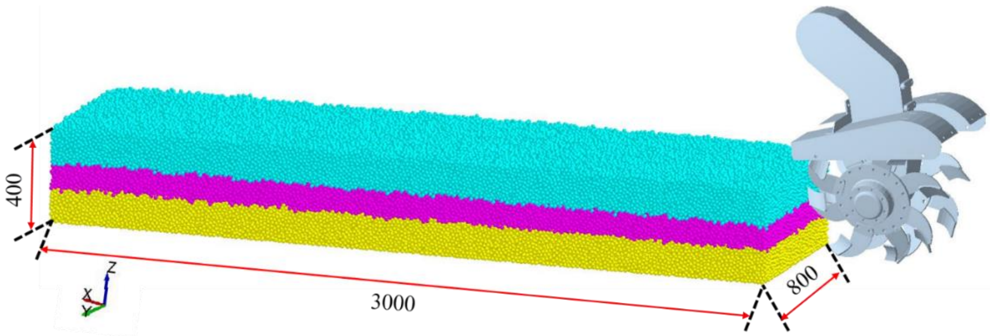


Fig. 3 - Simulation soil bin and geometric model of ditching device.

Determination and setting of soil particle contact parameters

The parameters of DEM simulation mainly include intrinsic parameters and contact parameters *(Kan Zheng et al, 2016)*. Among them, intrinsic parameters include shear modulus, density, and Poisson's ratio of orchard soil and ditching device; contact parameters include static friction coefficient, dynamic friction coefficient, and recovery coefficient between soil-soil and soil-steel. Simulation parameters directly affect the accuracy of the results. To accurately grasp the parameters of the test and simulation, the value of each parameter is determined based on the method of combining the test with the reference. Among them, the soil density is obtained by actual measurement with the ring knife method. The static friction coefficient and dynamic friction coefficient of 65Mn-soil and soil-soil were measured by inclined test-bed. Soil-soil surface can determine the corresponding values in EDEM according to the previous parameters, stacking angle test, and particle radius; other parameters refer to the data in reference *(Xuezhen Wang et al, 2018; Kan Zheng et al, 2016)*, and simulation parameters, as shown in Table 1.

Table 1

EDEM simulation parameters of ditching operation

Material	parameter	value	source
soil	Density/kg·m^{-3}	1669	determination
	Poisson's ratio	0.40	Reference [23]
	Shear modulus/MPa	1.0	Reference [23]
65Mn	Density /kg·m^{-3}	7.82×10^3	Reference [23]
	Poisson's ratio	0.29	
	Shear modulus/MPa	8.19×10^4	

65Mn-soil	Coefficient of restitution	0.6	Reference [24]
	Static friction coefficient	0.5	determination
	Dynamic friction coefficient	0.11	determination
soil-soil	Coefficient of restitution	0.6	literature [24]
	Static friction coefficient	0.4	determination
	Dynamic friction coefficient	0.15	determination
	JKR/J·m^2	2.3	Test calibration

Simulation process

To better characterize the influence of working parameters on the working state, the ditching depth was fixed at 350mm. Taking a certain working condition as an example, the pre-test is carried out. Set the parameters of the machine in EDEM: the forward speed v is 1.1m/s, and the direction is along the direction of the machine; the rotation speed of ditching cutter n is 385 r/min, and it rotates clockwise around the positive direction of the y-axis; the angle of the ditching cutter α is 35°. The parameters of the simulator module in EDEM software are set as follows: time step 20% (i.e. 2.06×10^{-4} s), action time 3.5 s, the interval time of data storage 0.05 s, and grid cell size 2 times the average particle radius. In EDEM, the operation status of the orchard ditching-fertilizer machine is shown in Figure. 4.

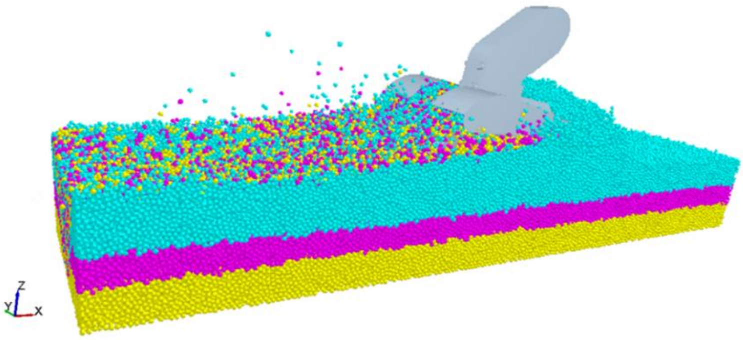


Fig. 4 - Status of orchard ditching

Analysis of simulation results

According to the working parameters and simulation parameters set in Table 1, the simulation test is carried out in EDEM. After the test, the depth of ditching and the number of particles covered with soil were measured and counted in EDEM post-processing. Among them, the ditching line of ditching is the fitting straight line of the transverse position of the deepest ditching. The ditching depth h is the distance from the ditching bottom line to the horizon, the sideline of the ditching contour is the line fitted by the side part of the ditching contour. According to the calculation formula of ditching depth stability coefficient y_1 and soil coverage rate y_2, the corresponding values are calculated, which are used as indicators to evaluate the effect of the ditching device, as shown in Figure 5. In the pretest, the stability coefficient of ditching depth y_1 and the coverage rate y_2 is 97.44%, 72.78% respectively.

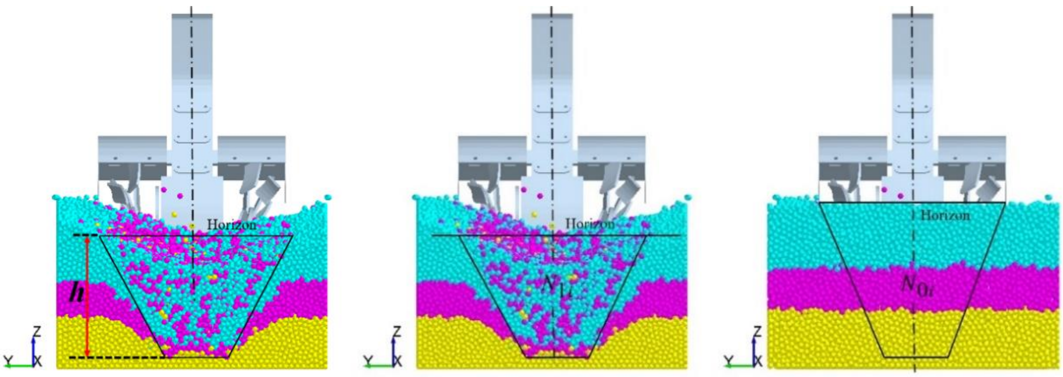


Fig. 5 - Measurement of various indexes in ditching operation

Experimental design

To explore the interaction and influence law of the three parameters, including forwarding speed, the rotation speed of the ditching cutter, and the deflection angle of the ditching cutter, on the stability of ditching depth and soil coverage rate.

Box-Behnken test design was used to carry out experimental research on operating parameters of the orchard ditching-fertilizer machine, and to seek the optimal working conditions for ditching operation parameters of orchard ditching-fertilizing machine method *(Jinqing Lu et al, 2016)*. According to the results of the orthogonal test, forward speed v, the rotation speed of the ditching cutter n, and the deflection angle of the ditching cutter α are set as independent variables x_1, x_2, and x_3 respectively. The stability coefficient of ditching depth and the coverage rate are set as y_1, y_2 respectively.

The experimental factors and coding levels of three factors and two levels are formulated, as shown in Table 2, and the results of the orthogonal test are shown in Table 3.

Table 2

Table of factor sand levels

levels	forward speed x_1/(m·s^{-1})	speed of the ditching cutter x_2/(r·min^{-1})	deflection angle of the ditching cutter x_3/(°)
low-level	0.8	320	25
mid-level	1.0	385	35
high-level	1.2	450	45

Table 3

Experimental design and results of ditching operation

Test number	x_1/(m·s^{-1})	x_2/(r·min^{-1})	x_3/(°)	y_1/(%)	y_2/(%)
1	1.0	450	45	93.99	74.49
2	1.0	450	25	96.44	75.54
3	1.2	450	35	97.61	70.77
4	1.2	385	25	95.42	73.26
5	1.0	385	35	96.99	74.31
6	0.8	385	45	96.10	82.76
7	1.0	320	45	94.87	77.92
8	1.0	385	35	97.54	74.03
9	1.0	320	25	95.41	79.17
10	1.2	385	45	97.98	71.89
11	0.8	450	35	94.77	77.64
12	0.8	385	25	97.12	81.51
13	0.8	320	35	98.34	82.60
14	1.0	385	35	96.91	73.81
15	1.0	385	35	97.61	74.99
16	1.2	320	35	94.11	74.65
17	1.0	385	35	96.51	75.40

RESULTS AND ANALYSIS

Establishment of the regression model and variance analysis

Design-Expert 8.0 software is used to establish a response surface regression model of forwarding speed, rotation speed of the ditching cutter, and deflection angle of the ditching cutter on the ditching depth stability coefficient and soil coverage rate. Variance analysis of the regression model is conducted, and the results are shown in Table 4.

It can be seen from Table 4 that the model significance *P* values of ditching depth stability coefficient and soil coverage rate are all less than 0.05, indicating that the regression model is significant. The *P* values of the mismatching items were all greater than 0.05, indicating that there was no mismatch factor, indicating that the regression equation had a high fitting degree, and the regression model could be used to replace the real test results for analysis. The order of significance of each factor on ditching depth stability is the deflection angle of the ditching cutter, forward speed, and rotating speed of the ditching cutter from large to small. The order of significance of influencing soil coverage rate is forward speed, the deflection angle of the ditching cutter, and the rotating speed of the ditching cutter. The R^2 of the model for the stability coefficient of the trench depth and the coverage rate are 0.8736, 0.9751, respectively, which indicates that 12.64% and 2.49% of the variation cannot be explained by the model. They indicated that the model has a good fitting degree and can be used for test prediction.

For the stability of ditching depth, the regression terms x_1x_2 had a significant impact ($P < 0.01$), and x_1x_3 and x_2^2 had a significant impact ($P < 0.05$). For the coverage rate, the regression terms x_1, x_2, x_3^2 had a significant impact ($P < 0.01$), and x_1^2 had a significant impact ($P < 0.05$).

Using Design-Expert 8.0 software to conduct multiple regression analysis on the test results in Table 4, the code value quadratic regression model of ditching depth stability and soil coverage rate affected by various factors is obtained, as shown in equations (6)~(7).

$$y_1=97.11-0.15x_1+0.01x_2-0.18x_3+1.77x_1x_2+0.89x_1x_3-0.48x_2x_3+0.29x_1^2-1.19x_2^2-0.74x_3^2 \quad (6)$$

$$y_2=74.51-4.24x_1-1.99x_2-0.30x_3+0.27x_1x_2-0.66x_1x_3+0.053x_2x_3+1.24x_1^2+0.67x_2^2+1.61x_3^2 \quad (7)$$

Variance analysis of regression model **Table 4**

evaluating indicator	Source of variance	Sum of squares	freedom	mean square	*P*	Significance
Stability coefficient of ditching depth y_1/(%)	model	25.85	9	5.38	0.0187	*
	x_1	0.18	1	0.34	0.5778	
	x_2	0.00	1	0.00	0.9682	
	x_3	0.26	1	0.49	0.5046	
	x_1x_2	12.47	1	23.34	0.0019	**
	x_1x_3	3.19	1	5.97	0.0446	*
	x_2x_3	0.92	1	1.71	0.2320	
	x_1^2	0.35	1	0.65	0.4476	
	x_2^2	5.96	1	11.16	0.0124	*
	x_3^2	2.32	1	4.34	0.0757	
	residual	3.74	7			
	Mismatch term	2.88	3	4.49	0.0903	
	Pure error	0.86	4			
	sum	29.59	16			
Coverage rate y_2/(%)	model	199.44	9	30.41	< 0.0001	**
	x_1	143.95	1	197.51	< 0.0001	**
	x_2	31.62	1	43.38	0.0003	**
	x_3	0.72	1	0.99	0.3519	
	x_1x_2	0.29	1	0.40	0.5491	
	x_1x_3	1.72	1	2.37	0.1679	
	x_2x_3	0.01	1	0.02	0.9053	
	x_1^2	6.47	1	8.88	0.0205	*
	x_2^2	1.87	1	2.56	0.1534	
	x_3^2	10.85	1	14.88	0.0062	**
	residual	5.10	7			
	Mismatch term	3.32	3	2.49	0.1999	
	Pure error	1.78	4			
	sum	204.55	16			

*Note: * indicates significant effect, P < 0.05; * * indicates extremely significant effect, P < 0.01.*

The model y_1 and y_2 are optimized by eliminating the insignificant items in the model, as shown in equation (7) ~ (8).

$$y_1=97.11+1.77x_1x_2+0.89x_1x_3-1.19x_2^2 \quad (7)$$

$$y_2=74.51-4.24x_1-1.99x_2+1.24x_1^2+1.61x_3^2 \quad (8)$$

Analysis of the interaction effect of two factors

In the regression Equation (6) ~ (7), taking any factor level as the medium level, and the influence of the other two factors on the stability coefficient of ditching depth, the soil coverage rate is studied. The response surface of interaction factors is analyzed by Design-Expert 8.0 software, as shown in Figure 7~8.

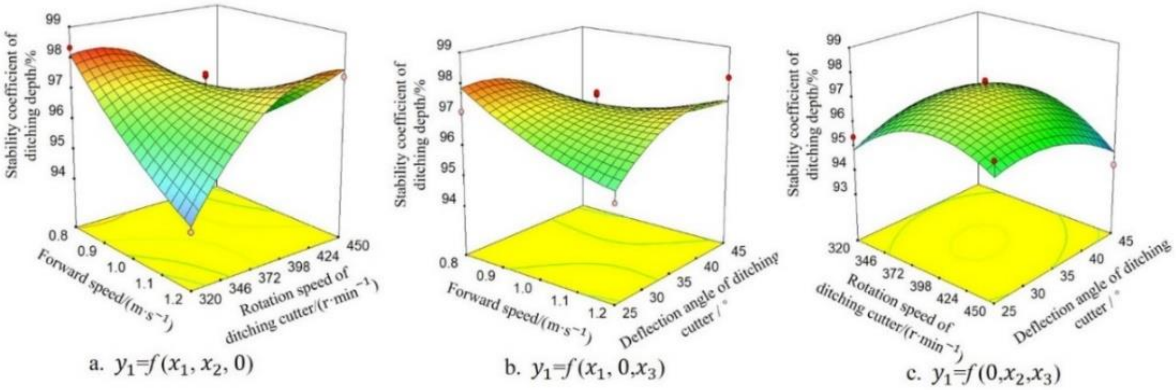


Fig. 7 - Response surfaces of test factors influence on ditching depth stability

Figure 7a shows the interactive influence of the forward speed and the rotation speed of the ditching cutter on the stability coefficient of the ditching depth. When the forward speed is at a low level, the impact of the rotation speed of the ditching cutter on the stability coefficient of the ditching depth is obvious, which is shown in the figure that the stability curve of the ditching depth is steep. When the forward speed is in the range of 0.8 ~ 1.0m/s, the stability of the ditching depth can be significantly improved by properly reducing the rotation speed of the ditching cutter. It can also be seen that when the rotation speed of the ditching cutter is the same, the stability of the ditching depth gradually decreases with the increase of the machine's forward speed. The stability of the ditching depth increases first and then decreases with the increase of the speed of the machine. Figure. 7b shows the interactive influence of the forward speed and the deflection angle of the ditching cutter on the stability of the ditching depth. The stability of the ditching depth decreases with the increase of the forward speed of the machine under the same deflection angle of the ditching cutter. The stability of the ditching depth increases at first and then decreases with the increase of the deflection angle of the ditching cutter at the same forward speed of the machine. Figure. 7c shows the interactive influence of the ditching cutter speed and the ditching cutter deflection angle on the ditching depth stability. Under the same ditching knife deflection angle, the ditching depth stability increases with the increase of the whole machine speed At the same speed of the cutter, the stability of the ditching depth increases first and then decreases with the increase of the forward speed of the whole machine.

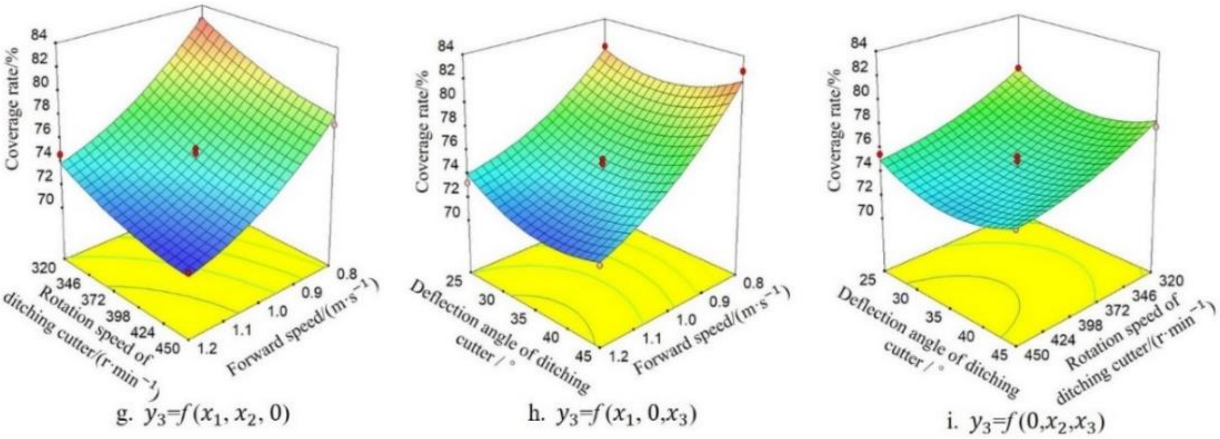


Fig. 8 - Response surfaces of test factors influence on coverage rate

Figure 8g shows the interaction between the forward speed and rotation speed of the ditching cutter on the soil coverage rate. When the rotation speed of the ditching cutter is at a low water level, the influence of the forward speed on the coverage rate is obvious, which is shown in the figure that the curve of the covering rate is steep. When the rotation speed of the ditching cutter is in the range of 320-372r/min, the covering rate can be significantly increased by a proper small forward speed. However, when the rotation speed of the cutter and the forward speed is reduced, the cover rate will increase obviously. Figure 8h shows the interaction between the forward speed and the deflection angle of the ditching cutter on the covering rate. Under the same forward speed, the covering rate decreases first and then increases with the increase of the deflection angle of the ditching cutter. At the same deflection angle of the ditching cutter, the covering rate decreases with the increase of the forward speed. Figure 8i shows the interaction between the rotation speed of the ditching cutter and the deflection angle of the ditching cutter on the covering rate. Under the same rotation speed of the cutter, with the increase of the deflection angle of the ditching cutter, the soil coverage rate first decreases slowly and then increases slowly. Under the same deflection angle of the ditching cutter, the rate of covering soil decreases with the increase of the rotation speed of the ditching cutter.

Parameter optimization

According to the agronomic requirements of orchard ditching operation, combined with the actual situation of orchard ditching-fertilizer machine ditching operation, it is required that ditching depth stability and soil coverage rate reach the optimal level. Due to the inconsistent influence of various factors on the target value, global multi-objective optimization is needed *(Chao Cheng et al, 2016; Wenxiu Zheng et al, 2019)*. Taking the stability of ditching depth and soil coverage rate as objective functions, the forward speed, the rotation speed of the ditching cutter, and the deflection angle of the ditching cutter are optimized. The optimized mathematical model is as follows

$$\begin{cases} \max y_1 = (x_1, x_2, x_3) \\ \max y_2 = (x_1, x_2, x_3) \\ st. \begin{cases} 0.8 \le x_1 \le 1.2 \text{ m/s} \\ 320 \le x_2 \le 450 \text{ r/min} \\ 25 \le x_3 \le 45\ ° \end{cases} \end{cases} \tag{9}$$

To find the best combination of parameters, the influence of three factors on the stability of ditching depth and the coverage rate is comprehensively considered. The optimal working parameters were obtained as follows: the forward speed was 0.8 km/h, the rotation speed of the ditching cutter was 348.03 r/min, and the deflection angle of the ditching cutter was 32.23° under these conditions, the stability of the ditching depth was 98.33%, and the covering rate was 81.53%.

Verification test

According to the optimization results of the ditching operation parameters of the orchard ditching-fertilizer machine, a field verification test was carried out to test the reliability of the regression model and optimal combination. 2FQG-2 orchard ditching-fertilizer machine developed by Shandong Agricultural University was used in the experiment. The structure of the machine is the same as the test prototype used in this paper. The test site is the test base of Gaomi Yifeng Machinery Co., Ltd. The soil is loam soil, the absolute moisture content is 16.7%, the ground is relatively flat, and the area is about 650m^2, as shown in Figure 9.

Fig. 9 - Validation test in the field

To facilitate the practical application, the optimized parameters are rounded properly. The forward speed is set as 0.8km/h, the rotation speed of the ditching cutter is 348r/min, and the deflection angle of the ditching cutter is 32°. The test methods and indicators refer to GB/T5262-2008 general provisions for determination of test conditions of agricultural machinery and the operation quality evaluation test method of ditching machinery specified in NY/T740-2003 *(2006, 2008)*. After three repeated tests, the average value is obtained. The stability of the ditching depth is 96.24%, and the coverage rate is 79.14%. The comparison between the predicted value and the measured test result is shown in Table 5.

Table 5

Comparison of predicted values of test indexes with measured results

index	stability of ditching depth y_1/%	coverage rate y_2/%
Optimization value	98.33	81.53
Test value	96.24	79.14
Relative error	2.17	3.02

The experimental results show that the relative errors between the measured values and the predicted values are less than 5%, and the measured values are in good agreement with the predicted values, indicating that the regression model is reliable.

CONCLUSIONS

(1) To obtain the optimal parameters of the orchard ditching-fertilizer machine, Box-Behnken experimental design was adopted. The forward speed, the rotation speed of the ditching cutter, and the deflection angle of the ditching cutter were set as independent variables. The stability of the ditching depth and the soil coverage rate were set as the response values. Through the analysis of the model interaction and response surface, the influence of the forward speed, the rotation speed of the ditching cutter, and the deflection angle of the ditching cutter on the response index are obtained.

(2) The optimization model of operation parameters of the orchard ditching-fertilizer machine was established. The optimal parameters of ditching depth stability and soil coverage rate were obtained: the forward speed was 0.8 km/h, the rotation speed of the ditching cutter was 348 r/min, and the deflection angle of the ditching cutter was 32°. At this time, the stability of the ditching depth is 98.33% and the coverage rate is 81.53%. The results show that the relative errors between the measured values and the predicted values are less than 5%, which indicates that the regression model is reliable.

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