PARAMETER OPTIMIZATION AND EXPERIMENT OF BRUSH ROLL GRAPEVINE COLD-PROOF SOIL CLEARING DEVICE
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刷辊式葡萄藤防寒土清土装置参数优化与试验研究

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ABSTRACT
Aiming at the problems of low efficiency, and low degree of mechanization of artificial soil clearing and considering that grapevines are easy to be damaged in northern China, a brush roll grapevine cold-proof soil clearing device suitable for removing soil in northern grape planting areas is studied and designed. The machine is mainly composed of a suspension device, soil removing device, hydraulic control system, telescopic device, etc. In this paper, a brush roll grapevine cold-proof soil clearing device was fabricated to investigate critical parameters such as rotation rate of soil removing device, brush spacing, and brush wire length on the machine performance. The three-factor and three-level quadratic regression orthogonal tests were carried out with the rotation rate of soil removing device, brush spacing, and brush wire length were taken as experimental factors and the soil removal rate and soil clearing distance were used as the evaluation indexes of soil clearing effect. The results show that the influence order of three factors on the soil removal rate was: rotation rate of soil removing device > brush spacing > brush wire length. The order of influence on the soil clearing distance was: rotation rate of soil removing device > brush wire length > brush spacing. The results show that when the rotation rate of the soil removing device was 248.71 r/min, brush spacing was 18.84 mm and brush wire length was 329.3 mm, the soil removal rate was 91.62% and the soil clearing distance was 11.63 cm. The relative error between the experimental verification value and the theoretical optimization value is less than 4%. This study provides the theoretical basis for the development of other types of grapevine cold-proof soil clearing devices.

摘要
针对中国北方地区人工清土效率低、机械化程度低、葡萄藤容易受损等问题，研究设计了一种适用于北方葡萄种植区的刷辊式葡萄防寒清土装置。该装置主要由悬挂装置、除土装置、液压控制系统和伸缩装置等组成。本文制作了刷辊式葡萄防寒清土装置，研究了除土装置的转速、刷子间距和刷丝的长度等关键参数对机器性能的影响。以除土装置的转速、刷子间距和刷丝的长度为实验因素，进行了三因素和三级二次回归正交试验，以清土率和清土距离为清土效果的评价指标。结果表明，三个因素对除土率的影响顺序为：除土装置转速>刷子间距>刷丝长度；对清土距离的影响顺序为：除土装置转速>刷丝长度>刷子间距。结果表明，当除土装置的转速为248.71r/min，毛刷间距为18.84mm，刷丝长度为329.3mm时，除土率为91.62%，清土距离为11.63cm。实验验证值与理论优化值之间的相对误差小于4%。本研究为开发其他类型的葡萄防寒清土装置提供了理论依据。

INTRODUCTION
Xinjiang is very suitable for growing grapes with superior quality by its unique geographical location and climate conditions (*Peng., 2020*). According to China Statistical Yearbook 2021 Annual Statistics, in Xinjiang the grape output was 3.056 million tons, accounting for 21.35% of the total grape production in China. The grape industry has become an important pillar of regional economic growth in Xinjiang (*Fu et al., 2021*). However, grapevines are vulnerable to cold damage at low temperatures (*Li et al., 2020; Yang et al., 2012*). Some very good management methods can help reduce the risk of incurring cold damage during the winter (*Li et al, 2013*). For instance: planting cold-hardy cultivars (*Sartori et al, 2015*); deferred pruning; planting windbreaks around a vineyard; painting the sides of grapevines (*Liu et al., 2019; Pezzi et al., 2015*); burying grapevine with soil; spraying medicine onto unpruned grapevine (*Shi et al., 2019*); and wrapping the grapevine with cold-proof cloth (*Ma et al., 2020*).

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The most commonly adopted method for protecting grapevine in Xinjiang is first wrapping the grapevine with cold-proof cloth and then covering the top of the cold-proof cloth with soil, which is an efficient environmentally friendly method for grapevine protection. Every winter, the grapevine is removed from the trellis and laid on the ground to be wrapped with cold-proof cloth and covered the top of the cold-proof cloth with soil for heat preservation (*Xu et al., 2019*). Every spring, the soil needs to be removed in time, and it is necessary to avoid damaging grapevines during removal. Thus, the cold-proof soil removal mainly depends on human removal, which is high in labour intensity, has low efficiency and high cost.

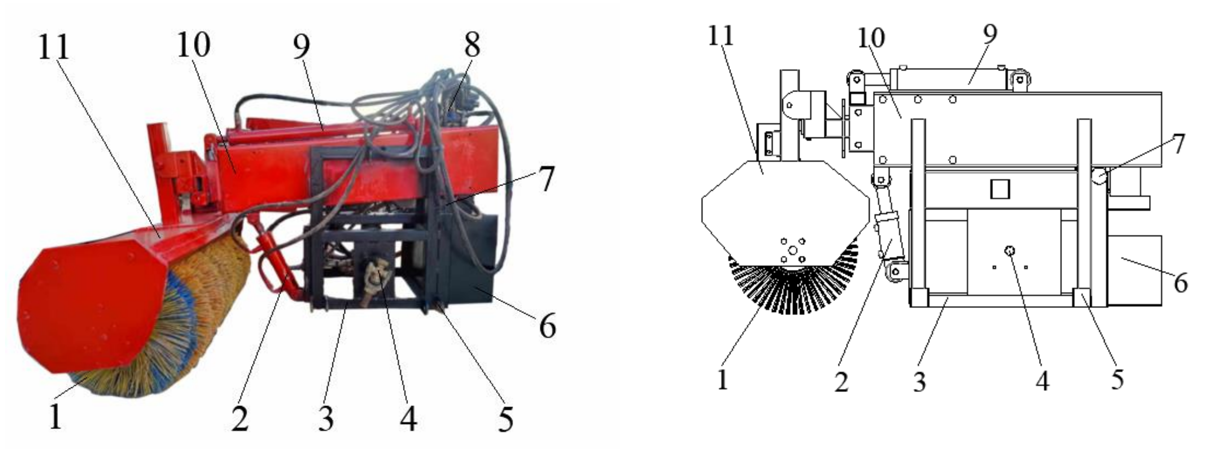
Relevant research has been carried out on cold-proof soil clearing machines at home and abroad (*Gambella et al., 2015*). Overseas, because of the mild and humid climate in foreign grape planting areas, there is no need to bury soil to prevent cold in winter and clear soil in spring, so there are few references on grape cold-proof soil clearing machines in foreign countries (*Caprara et al., 2014*). In recent years, due to the increasing planting area scale, domestic scholars have conducted research on cold-proof soil clearing machines and achieved many results. The layered-staggered structure was designed (*Ma et al., 2021*). It can complete multiple operations at one time. The trellis-type grape winter buried soil clearing and cold-proof cloth recycling machine were developed (*Niu et al., 2020*). The operation efficiency of the machine was more than 10 times the manual soil clearing efficiency. The automatic obstacle-avoiding grapevine cold-proof soil cleaners were designed (*Ma et al., 2020; Liu et al., 2018*), which meet the requirements of automatic obstacle-avoiding grapevine cold-proof soil clearing. The unilateral cleaning machine for grapevine buried by soil with a rotary impeller was developed (*Ma et al., 2018*), which satisfies the operation requirements for unilateral soil cleaning of grapevines. The grapevine machine was developed (*Zeng et al., 2013*). The machine structure design is reasonable, the layout is compact, it is low cost and supposes easy operation and maintenance. The type of grapevine cleaning soil machine was designed (*Xie et al., 2016; Wang et al., 2015*). The working principle and essential components for the machine were analysed. The type of conical spiral spring grapevine digging machine was developed (*Liu et al., 2014*), which meets the design requirements for soil digging.

In summary, considering the existing cold-proof soil clearing machines in Xinjiang they showed some drawbacks, such as low efficiency, low degree of mechanization, and poor soil clearing performance. A kind of brush roll grapevine cold-proof soil clearing device was developed and tested to improve operational efficiency and reduce labour costs. The interaction process between the soil removing device and soil in the vineyard was analysed. This study was expected to provide a valuable reference for the design of grapevine cold-proof soil clearing machine cost.

MATERIALS AND METHODS

Overall structure

The brush roll grapevine cold-proof soil clearing device mainly consists of a suspension device, soil removing device, a hydraulic control system, a telescopic device, etc. The overall structure is illustrated in Figure 1, and the main technical parameters of the whole machine were shown in Table 1.



(a) (b)

Fig. 1 - Schematic diagram of brush roll grapevine cold-proof soil clearing device
(a) prototype machine; (b) front view

1 – Flexible brushes; 2 – Height adjustment hydraulic cylinder; 3 – Frame; 4 – Power input shaft; 5 – Three-point suspension device; 6 – Counterweight box; 7 – Rotating shaft; 8 – Hydraulic system; 9 –Telescopic hydraulic cylinder; 10 – Telescopic arm; 11 – Soil removing device

Table 1

Main technical parameters

Parameter	Value	Units
Overall dimension (length × width ×height)	1550×1400×775	mm
Tractor power	≥58	kW
Operation speed	1~3	Km/h
Operating width	1500	mm
Driving form	Hydraulic drive	-
Hanging and connection form	Three-point suspension	-
Number of working row	1	-

Working principle

During the cold-proof soil removing operation, the brush roll grapevine cold-proof soil clearing device is hung behind a four-wheel tractor through a three-point suspension device. The power of the tractor is input into the hydraulic pump and transmitted to the hydraulic motor which drives the soil-removing device to rotate synchronously to remove inter-row soil at the vineyard. Firstly, the height of the soil clearing device is adjusted by a height adjustment hydraulic cylinder, to ensure that the machine height meets the operation requirements; meanwhile, the corresponding rotation rate of the soil removing device could be easily adjusted by controlling the speed of the hydraulic motor through a flow control valve. Then the soil removing device entered into the soil and removed inter-row soil. Finally, the telescopic device could continuously reciprocate movement at a suitable speed to convey the soil to the side of the machine. In this way, the operation of the soil clearing device is realized.

Motion analysis of soil clearing device

The soil removing device is powered to move around a shaft and move leftward. The motion of the soil removing device can be regarded as the combined motion of a uniform linear motion and uniform circular motion around the axis. Schematic analysis of soil clearing device motion is shown in Figure 2. The soil is removed under the joint action of the telescopic device reciprocating speed v_m and the soil clearing device linear speed v_t. The coordinate system was established with the centre of the soil clearing device as the origin, the right side of the x-axis as the positive direction, and the vertical direction of the y-axis as the positive direction.

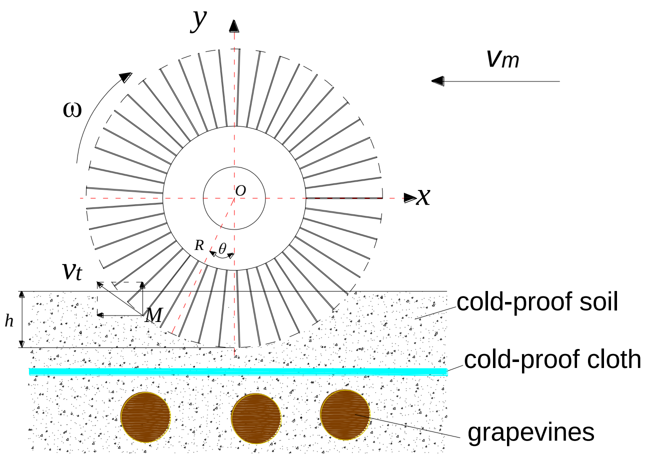


Fig. 2 - Schematic analysis of soil clearing device motion

Thus, the equation for the motion trajectory of point *M* can be represented as follows:

$$\begin{cases} x = v_m + R\cos\theta \\ y = R\sin\theta \end{cases} \tag{1}$$

Where:

$$\theta = \omega \cdot t \tag{2}$$

where:

v_m is the retraction speed of the telescopic device, [m/s];

R is the brush wire length, [mm];

θ is the rotation angle of the soil clearing device, [rad];

h is the clearing depth, [mm]; t is the rotating time of the soil clearing device, [s];

ω is the angular velocity of soil clearing device movement, [rad/s].

The split velocity of point M in the horizontal and vertical directions is as follows:

$$\begin{cases} v_x = dx/dt = v_m - R\omega\, sin(\omega \cdot t) \\ v_y = dy/dt = R\, cos(\omega \cdot t) \end{cases} \tag{3}$$

The instantaneous velocity of point M is as follows:

$$v_t = \sqrt{v_x{}^2 + v_y{}^2} \tag{4}$$

Substituting Equation (3) into Equation (4), an equation can be obtained and the instantaneous velocity of point M is as follows:

$$v_t = \sqrt{v_x{}^2 + v_y{}^2} = \sqrt{v_m{}^2 + (R\omega)^2 - 2v_m R\, sin(\omega \cdot t)} \tag{5}$$

According to the schematic diagram of the structure in Figure 2, the following equation can be obtained:

$$cos(\omega \cdot t) = \frac{R-h}{R} = 1 - \frac{h}{R} \tag{6}$$

According to the analysis results in formulas (4) and (5), the main factors impacting the soil clearing performance of the brush roll grapevine cold-proof soil clearing device include the rotation rate of soil removing device, telescopic device retraction speed, brush wire length, brush spacing, angular velocity, elastic deformation of the flexible brushes. Based on the previous field trials, the reciprocating speed of the telescopic device is not considered because it changes very little during operation. This test mainly selects the rotation rate of the soil removing device, brush wire length and brush spacing.

If the rotation rate of the soil removing device is too high, it would lead to the damage of grapevines, but if it is too low, it cannot meet operation requirements. According to the previous field trials, the rotation rate of the soil removing device is designed and calculated to be 200 ~ 300 r/min. If the brush wire length is too long, it would cause higher energy consumption, but if it is too short, it may lead to incomplete soil removal. As a result, the brush wire length of the soil removing device is designed to be 275 ~ 375 mm, the brush wire length could be adjusted by replacing brushes with different diameters. The brush spacing can directly affect the soil removal rate and soil clearing distance. If brush spacing is too large, the soil falls easily, resulting in leakage and affecting the quality of soil clearing. If the brush spacing is too small, it is easy to damage the grapevines, causing problems such as energy consumption and soil plugging. Thus, the brush spacing of the soil removing device is designed to be 10 ~ 30 mm.

Type selection design of the hydraulic system

To acquire stable reliable power, considering economic efficiency and convenience, the brush roll grapevine cold-proof soil clearing device adopts the hydraulic system driving mode. The overall hydraulic system consists of the telescopic system and the clearing system. During work, the soil clearing parts need to keep a stable rotation speed, which can be achieved by manually adjusting the throttle valve. The hydraulic system was adopted, as it has high efficiency, structural concision, easily adjustable speed range and is suitable for complex environments in the field. A schematic diagram of the hydraulic system is shown in Figure 3.

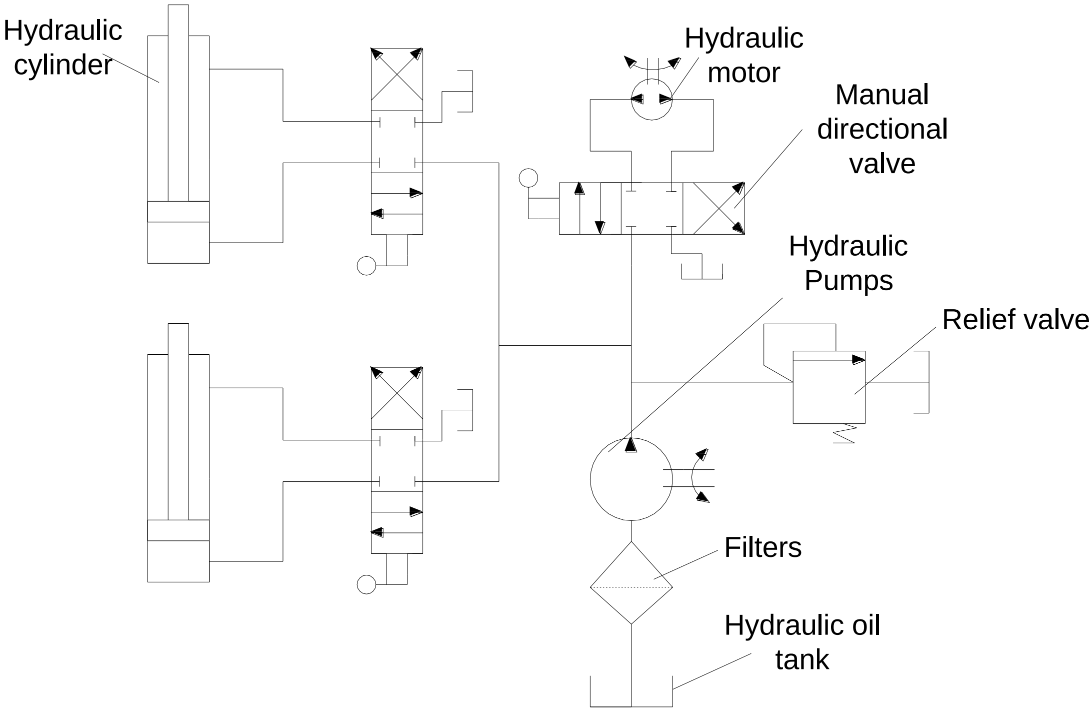


Fig. 3 - Schematic diagram of hydraulic system

Parameter measurement of physical parameters

In addition, the physical parameters of the soil ridge of soil buried grapevine can provide a theoretical basis for the manufacture of the machine. The test area used in this measurement was located in a vineyard of the Huaxing Farm in Changji. Soil ridge depth of soil buried grapevine was 30~40 cm, and soil ridge width of soil buried grapevine was 90~100 cm. The measurement process is shown in Figure 4.

(a) (b) (c)

Fig. 4 - Measurement of physical parameters: (a) measurement of soil ridge depth; (b) measurement of soil spacing; (c) measurement of soil moisture

Test conditions

Currently, the Xinjiang and other main grape-producing areas mostly adopt the planting mode of trellis-type planting, the row spacing of grapevines is between 3.0~4.0 m, and the plant spacing is between 1~1.5 m. To verify the soil removing performance of the machine, the experiment was carried out in the test base of Huaxing Farm in Changji in December 2021. The weather was sunny, the soil moisture content was between 3.1% and 12.5% and the soil hardness was 3.5~6.2 kg/cm^2, the soil in the test site was sandy soil and the test field was flat, loose with few weeds. The test site is shown in Figure 5. The matching power of the working machine was 58.9 kW Huayuan-804 wheeled tractor. The main instruments and equipment used in the field test were brushed roll grapevine cold-proof soil clearing device, TYD-2 soil hardness tester, QS-WT soil moisture tester, rotational Speed Tester, tape measure, wrench, etc.

(a) (b) (c)

Fig. 5 - Test of brush roll grapevine cold-proof soil clearing device;
(a) experimental prototype; (b) before clearing; (c) after clearing

Evaluation of soil cleaning effect

The cold-proof soil clearing operation schedule of the brush roll grapevine cold-proof soil clearing device was designed. The operation length of a single row was 85 m, the first 5 m of which represented the acceleration zone, the last 5 m the deceleration zone, and the middle 75 m the data test zone in the field. Each row along the forward direction was divided into 50 sections as the measuring area according to the continuous length of 1.5 m, and the test areas could not be repeated. Firstly, to ensure that the test results were accurate and reliable, before the test, the machine had to be strictly inspected to ensure that it was installed firmly and reliably so as not to affect the test results and the rotation rate of soil removing device was adjusted according to the test requirements. Then the brush roll grapevine cold-proof soil clearing device entered the working state. Finally, every time soil clearing was completed in a measuring area, the machine status had to be checked. The soil removal rate was calculated according to formula (7), after the completion of all measurement areas.

The calculation formula for soil removal rate is as follows:

$$\left\{ G = \frac{Q - Q_1}{Q} \times 100\% \right. \tag{7}$$

Where:

G is the soil removal rate, [%];

Q is the total quality of cold-proof soil before the operation, [kg];

Q_1 is the quality of residual cold-proof soil after the operation, [kg].

Xinjiang grape planting has not yet formed a unified and standardized planting mode, thus the performance evaluation of the soil clearing machine is based on accomplished soil clearing operation, and there is no unified and quantitative index. In this paper, the distance between the inter-row soil distribution center line and the inter-row center line was defined as the soil clearing distance L to conduct the field experiments, and the minimum value of the distance between the inter-row soil distribution center line and the grape winter buried soil centerline was used as the optimal index. During the process of cold-proof soil clearing operation, the smaller the distance L was, the stronger the soil clearing ability of the machines. The schematic diagram of the soil clearing distance of the brush roll grapevine cold-proof soil clearing device is shown in Figure 6. In summary, the soil removal rate G and the soil clearing distance L were selected as the evaluation index.

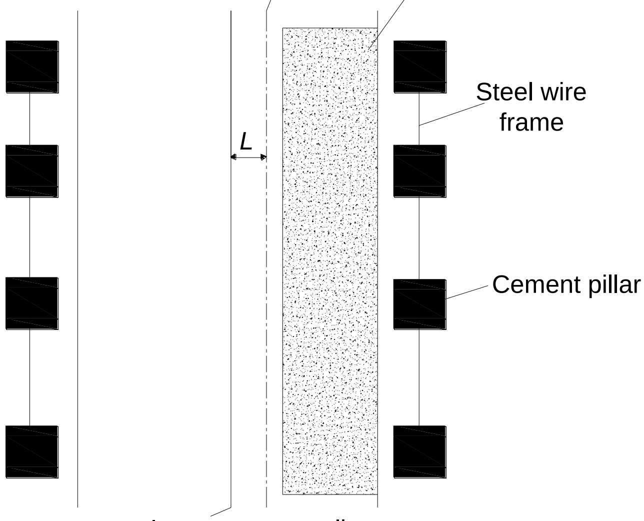


Fig. 6 - Schematic diagram of clearing distance

Test design

Based on the preliminary field experiment, the rotation rate of soil removing device *A*, brush spacing *B* and brush wire length *C* were selected as the test factors, and the soil removal rate and the soil clearing distance were used as the evaluation index. The Box-Behnken composite test design method was adopted, which was used to study their effect on the soil removal rate and soil clearing distance. The value range of each factor and the factors and levels in the test are shown in Table 2.

Table 2

Experimental factors and levels

Levels	**The rotation rate of soil removing device A**	**Brush spacing B**	**Brush wire length C**
	[r/min]	[mm]	[mm]
-1	200	10	275
0	250	20	325
1	300	30	375

The test mainly designs the three-factor three-level test plan using the Box-Behnken of Design-Expert. The response surface test plan and results are shown in Table 3.

Table 3

Box-Behnken design scheme and response value of clearing distance

Test number	**The rotation rate of soil removing device A**	**Brush spacing B**	**Brush wire length C**	**Soil removal rate**	**Soil clearing distance**
	[km/h]	**[r/min]**	**[mm]**	**[%]**	**[cm]**
0	**1**	**2**	**3**	**4**	**5**
1	-1	0	-1	81.65	15.45
2	-1	0	1	82.28	12.58
3	0	-1	1	88.48	14.26
4	-1	-1	0	86.25	16.48
5	0	1	-1	87.64	15.56
6	-1	1	0	78.17	13.84
7	0	0	0	90.52	12.35
8	0	0	0	92.65	10.28
9	0	0	0	91.67	11.45
10	0	-1	-1	86.42	17.64
11	0	0	0	92.54	12.65
12	1	-1	0	88.28	17.18

Table 3
(continuation)

0	1	2	3	4	5
13	0	1	1	79.45	14.65
14	1	0	-1	87.29	16.49
15	1	1	0	87.46	18.58
16	1	0	1	83.39	16.43
17	0	0	0	90.46	11.55

RESULTS AND ANALYSIS

Test analysis results

The Design Expert statistical analysis software was used to perform a polynomial regression analysis on the experimental data in Table 3. Through the analysis of the results in Table 3, the regression model equations of soil clearing distance L and soil removal rate G are fitted out respectively. The regression equation of the soil removal rate G and the soil clearing distance L was obtained as shown in formulas (8) ~ (9).

$$\begin{gathered} G = 91.57 + 2.26A - 2.09B - 1.18C + \\ 1.81AB - 1.13AC - 2.56BC - \\ 4.19A^2 - 2.34B^2 - 3.73C^2 \end{gathered} \quad (8)$$

$$\begin{gathered} L = 121.66 + 1.29A - 0.37B - 0.90C + \\ 1.01AB + 0.7AC + 0.62BC + \\ 2.29A^2 + 2.58B^2 + 1.29C^2 \end{gathered} \quad (9)$$

where, A is the rotation rate of soil removing device, [r/min]; B is brush spacing, [mm]; C is the brush wire length [mm].

Table 4

Variance analysis results

Source	Soil removal rate					Soil clearing distance				
	SS	DF	MS	F Value	P-Value	SS	DF	MS	F Value	P-Value
Model	303.75	9	33.75	28.69	0.0001	91.62	9	10.18	19.20	0.0004
A	40.82	1	40.82	34.70	0.0006	13.34	1	13.34	25.16	0.0015
B	34.90	1	34.90	29.67	0.0010	1.07	1	1.07	2.02	0.1978
C	11.05	1	11.05	9.39	0.0182	6.52	1	6.52	12.29	0.0099
AB	13.18	1	13.18	11.20	0.0123	4.08	1	4.08	7.70	0.0275
AC	5.13	1	5.13	4.36	0.0751	1.97	1	1.97	3.72	0.0950
BC	26.27	1	26.27	22.33	0.0021	1.53	1	1.53	2.88	0.1337
A^2	73.80	1	73.80	62.74	< 0.0001	22.02	1	22.02	41.54	0.0004
B^2	23.08	1	23.08	19.63	0.0030	27.96	1	27.96	52.74	0.0002
C^2	58.55	1	58.55	49.78	0.0002	7.06	1	7.06	13.31	0.0082
Lack of Fit	3.78	3	1.26	1.13	0.4363	0.29	3	0.098	0.11	0.9468
Pure Error	4.45	4	1.11			3.42	4	0.85		
Cor Total	311.98	16				95.33	16			

Note: SS is the sum of squares of deviations; DF is the degrees of freedom; MS is the average of the sum of squares of deviations; P<0.01 (Extremely significant,); P<0.05 (Significant).

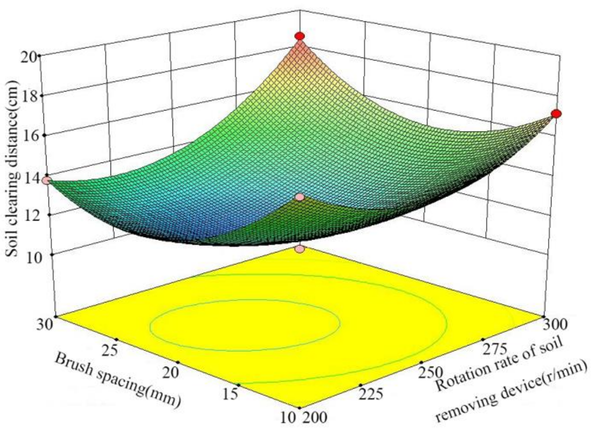
Significance test and variance analysis of mathematical model were carried out, and the results are shown in Table 4. According to the data results, the regression model was significant (P<0.05), indicating that the model established was meaningful. In the soil removal rate G model, the influence of other regression items is significant (P < 0.05), except AC, which is not significant (P > 0.05); in the soil clearing distance L model, except B, AC, and BC had no significant influence (P > 0.05), other regression items had significant influence (P < 0.05). According to the F value of each factor in Table 4, the influencing effects of the three factors on soil removal rate rank as A>B>C. The influencing effects of the three factors on soil clearing distance rank as A>C>B.

Response surface analysis

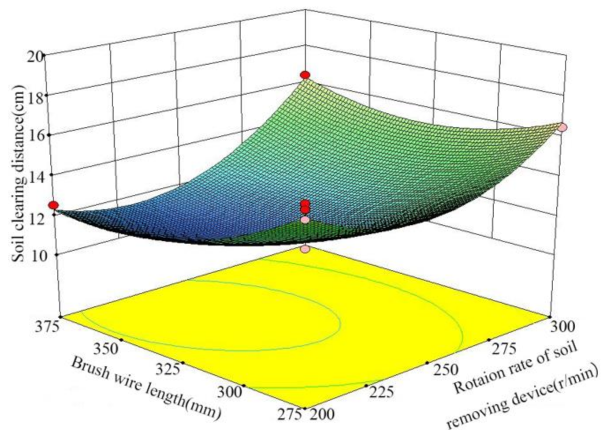
In Figure 7a, brush wire length is in the middle level, namely C=325 mm, the interactive effect of the rotation rate of the soil removing device and brush spacing on the soil clearing distance is shown, and it is clear that the interactive effect of the two factors is significant. In the case of the same brush spacing, the soil clearing distance decreases first and then increases with the increase of the rotation rate of the soil removing device; in the case of the rotation rate of the soil removing device, the soil clearing distance decreases first and then increases with the increase of the brush spacing. The impact of brush spacing on the soil clearing distance is smaller than that of the rotation rate of the soil removing device.

In Figure 7b, the brush spacing is in the middle level, namely B=20 mm, the interactive effect of the rotation rate of the soil removing device and brush wire length on the soil clearing distance is shown, and it is clear that the interactive effect of the two factors is not significant. In the case of the same rotation rate of soil removing device, the soil clearing distance decreases with the increase of the brush wire length; in the case of the brush wire length, the soil clearing distance decreases first and then increases with the increase of the rotation rate of soil removing the device. The impact of brush wire length on the soil clearing distance is smaller than that of the rotation rate of the soil removing device.

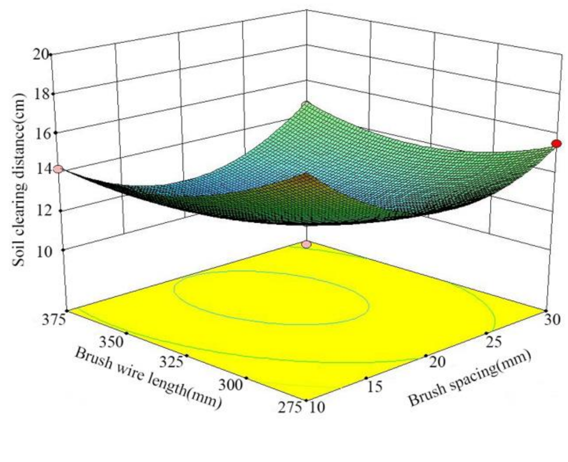
In Figure 7c, the rotation rate of the soil removing device is in the middle level, namely A= 250 r/min, the interactive effect of brush spacing and brush wire length on the soil clearing distance is shown, and it is clear that the interactive effect of the two factors is not significant. In the case of the same brush spacing, the soil clearing distance decreases first and then increases with the increase of the brush wire length; when the brush wire length is relatively low, the soil clearing distance decreases with the increase of brush spacing, while the brush wire length is relatively high, the soil clearing distance increases with the increase of the brush spacing, and the impact of brush spacing on the soil clearing distance is not as significant as the impact of brush wire length.



a) L=(A,B,0)



b) L=(A,0,C)



c) L=(0,B,C)

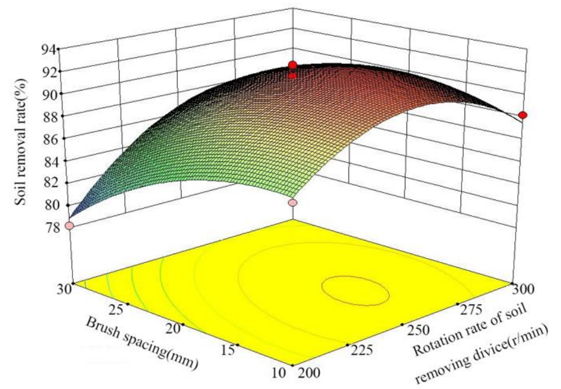
Fig. 7 – Response surface of different experimental factors to soil clearing distance effect

The response surface curves of the influence of the interactive factors, namely the rotation rate of soil removing device, brush spacing, and brush wire length, on soil removal rate are shown in Figure 8.

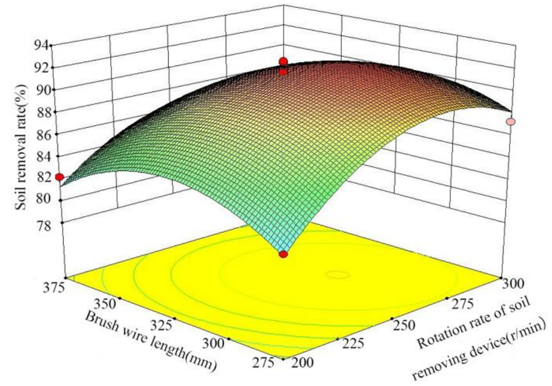
Figure 8a shows that the brush wire length remains at the intermediary level, that is, C=325 mm. It can be seen from Figure 8a that the interactive effects between the two factors are significant. In case of the same brush spacing, the soil removal rate increases first and decreases afterward as the rotation rate of soil removing device increases, because with the increase of soil removing device rotation speed, the soil removal rate to machine is increased. But if the rotation rate of the soil removing device is too high it is easy to damage the grapevines, causing problems such as grapevine injuries and higher energy consumption. In the case of the same rotation rate of the soil removing device, the soil removal rate decreases as the brush spacing increases, because the increase of brush spacing can lead to irregular clearing, missed clearing, and lower soil removal rate. The influence of brush spacing on soil clearing distance is not so significant as the rotation rate of the soil removing device.

As shown in Figure 8b, the brush spacing remains at the intermediary level, that is, B=20 mm. It can be seen from Figure 8b that the interactive effects between the two factors are not significant. Under the same brush wire length, the soil removal rate increases first and decreases then with the increase of the rotation rate of the soil removing device. Under the same rotation rate of soil removing device the influence of brush wire length on soil removal rate is relatively small.

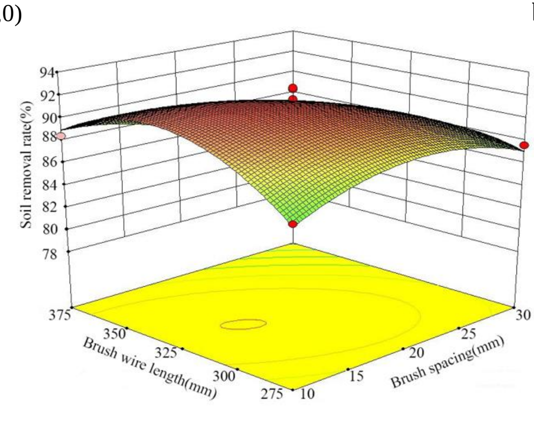
As shown in Figure 8c, the rotation rate of the soil removing device remains at the intermediary level, that is, A=250 r/min. It can be seen from Figure 8c that the interactive effects between the two factors are significant. Under the same brush wire length, the soil removal rate increases first and decreases then with the increase of brush spacing. Under the same brush spacing, the soil removal rate increases first and decreases then with the increase of brush wire length. Because the increase of brush wire length improves the soil feeding amount facilitating the soil removal. When the brush wire length is too long, it can increase the elastic deformation of the brush wire and lower the soil removal rate, and affect the quality of soil clearing.



a) G=(A,B,0)



b) G=(A,0,C)



c) G=(0,B,C)

Fig. 8 – Response surface of different experimental factors to soil removal rate effect

Parameter optimization and validation

Combined with the analysis above, to optimize the performance of brush roll grapevine cold-proof soil clearing device, it is required a minimum soil clearing distance and maximum soil removal rate. To obtain the best working parameters of the brush roll grapevine cold-proof soil clearing device, the minimum soil clearing distance, and maximum soil removal rate was taken as the optimization objectives, and the optimization module in Design-Export software was used to solve the optimal parameters. The objective function and constraint conditions are shown in formula (10):

$$\begin{cases} MaxG \\ MinL \\ A \in [200-300r/\min] \\ B \in [10-30mm] \\ C \in [275-375\text{mm}] \end{cases} \tag{10}$$

After optimization calculation, the optimal working parameters were obtained as follows the rotation rate of soil removing device was 248.71 r/min, the spacing of brushes was 18.84 mm, and the length of brush wire was 329.3 mm. The predicted values of removal rate and clearing distance of grape cold-proof soil were 91.62% and 11.63 cm respectively. The validation experiment was carried out with the above optimization parameters. The results showed that the removal rate of grapevine cold-proof soil was 90.8%, and the soil clearing distance was 11.98 cm, which was consistent with the prediction result of the model, and the prediction error was less than 4%.

CONCLUSIONS

(1) In this study, a brush roll grapevine cold-proof soil clearing device was developed and tested to study the effects of the rotation rate of the soil removing device, brush spacing, and brush wire length on soil clearing distance and soil removal rate of the machine. It was safe to conclude that the key factors affecting the performance of the brush roll grapevine cold-proof soil clearing device were determined: the rotation rate of the soil removing device, brush spacing, and brush wire length.

(2) The analysis of variance showed that the order of influence on the removal rate of cold-proof soil was rotation rate of soil removing device > brush spacing > brush wire length, and the order of influence on the clearing distance of cold-proof soil was rotation rate of soil removing device > brush wire length > brush spacing.

(3) Taking the maximum removal rate and minimum clearing distance of cold-proof soil as the optimization goal, the optimal working parameters were obtained: the rotation rate of the soil removing device was 248.71 r/min, brush spacing was 18.84 mm, and brush wire length was 329.3 mm. The predicted removal rate of cold-proof soil was 91.62%, and the predicted soil clearing distance was 11.63 cm. The experimental results show that the removal rate of cold-proof soil was 90.8% and the soil clearing distance was 11.98 cm, which was consistent with the prediction results of the model.

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