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ANALYSIS AND EXPERIMENT ON THE WORKING PROCESS OF SOIL-CULTIVATING DISC OF POTATO CULTIVATOR
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马铃薯中耕机培土圆盘工作过程分析与试验

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ABSTRACT

Aiming at the problems of the existing potato cultivator in cultivation, such as poor effect and easy damage to seedlings, the composition structure and tillage principle of the cultivator is analyzed. Furthermore, in order to determine the volume of soil thrown by the soil-cultivating disc, that is, the main tilling indexes of JB/T7864-1999"Test methods of cultivator-fertilizer", this study makes a theoretical analysis on the dynamics of tilling device and the kinematics of tilling operation, to obtain the structural and motion parameters affecting soil cultivation. The discrete element simulation software is used for single-factor simulation analysis, to obtain the linear relationship between each factor and soil cultivation. Taking the tillage depth, cultivator forward speed and disc diameter as the factors, and the soil cultivating height as the test index, a field three-factor and three-level orthogonal test was carried out, and the optimal parameter combination was selected. The results showed that with the increase of the disc diameter and tillage depth, the cultivating height increased, and with the increase of the cultivator forward speed, the cultivating height increased first and then decreased. Through the orthogonal test of factors and the analysis of range and variance, it is determined that when the tillage depth is 105 mm, the operating speed is 5.5 km/h and the disc diameter is 475 mm, the effect of soil-cultivating disc is optimal. The results are also verified by the field test, and it can lay a foundation for the optimal design of potato cultivator.

摘要

针对现有马铃薯中耕机在马铃薯中耕作业存在的作业效果不佳、易伤苗等问题，本研究在前人研究的基础上，对中耕机的组成结构及耕作原理进行了剖析，得到培土圆盘是影响马铃薯中耕作业的效果的重要因素。进而，为了明确影响马铃薯中耕机培土圆盘培土量，即 JB/T7864-1999《旱田中耕施肥机试验方法》中的主要中耕指标，本文对培土装置的动力学以及对培土作业运动学进行了理论分析，得出了影响培土作业效果的结构参数和运动参数。利用离散元仿真软件对培土作业进行单因素仿真分析，得到各试验因素与培土效果的线性关系。以同样的试验因素，即耕作深度、机车前进速度、圆盘直径为试验因素，以培土高度为试验指标，进行了田间三因素三水平正交试验，选取较优参数组合。试验表明：圆盘直径与耕作深度随数值增加，培土高度增大；机车前进速度增大，培土高度先增加后减小。通过对试验因素进行正交试验，对极差和方差进行分析，确定了耕作深度为105mm、作业速度为5.5km/h，圆盘直径为475mm 时，培土圆盘培土作业效果最佳，并进行了田间验证试验。本研究可为马铃薯中耕机得优化设计奠定基础。

INTRODUCTION

Potato is an economic crop with strong adaptability, rich nutrition and high yield, which is widely used in food processing and livestock feed industry. Potato has a high total output and a large planting area in China. It has been the fourth largest food crop and has great development potential.

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Potato cultivation refers to the cultivating operations of soil loosening, weeding, crushing and cultivating by cultivator in the potato seedling stage and the middle stage of growth. The purpose is to loosen soil, improve soil structure, enhance soil fertility, improve soil permeability, protect moisture and drought, and remove weeds *(Lv et al., 2015; Ribeiro et al., 2020; Liu, 2011; Kroupin and Semenov, 2018)*. During the potato cultivation, the early cultivation is particularly important and difficult. The reason is that the potato seedlings are immature during the early cultivation, and slight touch or environmental discomfort will easily lead to damage and affect the survival rate of the seedlings. If the soil height is too high, it is easy to cover the seedlings and cause damage; on the contrary, the potato seedlings will be exposed to the soil surface and the root nutrient supply will be insufficient. The factors that affect the soil-cultivating height include the tillage depth, forward speed, and the disc diameter and inclination angle of the soil-cultivating disc. The tilling device that is in direct contact with the soil is the soil-cultivating disc, whose dynamics and kinematics directly affect the quality of cultivation.

Researches on potato cultivators abroad are relatively early, and have high technical level and good reliability *(Hwang et al., 2021; Tang et al., 2021; Zheng et al., 2021; Qiu et al., 2020)*. The representative potato cultivators are the GH potato cultivator, from GRIMME, in Germany and the ZF potato cultivator, from STRUIK, in the Netherlands. They have good operation effect and are suitable for large plots in Europe and the United States. Due to the difference from domestic soil conditions, these cultivators are expensive and difficult to maintain, and not suitable for the national conditions. The domestic potato cultivator started late, but it has developed rapidly. The 1ZL5 potato cultivator, developed by *Lv, J. Q. et al.,* can complete soil loosening, weeding and ridge building in one operation *(Lv, 2017)*. The machine uses a hoe shovel cultivator with a large amount of soil, which is not suitable for operations requiring a small amount of soil in the early stage of potato emergence. The driven multi-function potato cultivator developed by *Lv, J. Q. et al.,* integrates soil crushing, fertilization, weeding and soil cultivation. It is suitable for potato fields with heavy soil conditions. The soil cultivator collects the soil thrown by the crushing knife and then cultivates the soil. However, the power consumption is excessive in the sandy loam plot. The 3ZF-3200/3 vertical rotary potato cultivator, developed by *Liu, E. H. et al.,* is mainly aimed at cultivating the heavy soil with hardened soil and excessive weeds. Due to the fragile potato seedlings during the pre-emergence operation, this machine is not suitable for potato cultivation in this period. According to the above research, it is found that the soil-cultivation components used in the existing potato cultivator are too large to be used for the first potato cultivation. In the early stage, the team designed a disc soil cultivation component suitable for the first cultivation of potatoes, and carried out relevant experiments. The results showed that the designed soil cultivating disc had significantly less soil than other soil cultivation components, whereas, the factors that affect the amount of soil cultivating have not yet been clearly identified.

During the development of potato cultivator, there are few experimental studies using soil-cultivating height, as the experimental index. Therefore, in order to optimize the cultivating performance of potato cultivator in this regard, this paper makes kinematic and dynamic analysis and single-factor simulation test on the working process of soil cultivating disc, to determine the level range of each factor. Furthermore, taking the tillage depth, forward speed, and disc diameter as test factors, and the soil-cultivating height as indexes, a three-factor and three-level orthogonal test was carried out at the Experimental Demonstration Base of Northeast Agricultural University in Harbin, Heilongjiang Province. Through the orthogonal test, the optimal level combination affecting the soil height was determined, and the verification test was carried out.

MATERIALS AND METHODS

The whole cultivator is mainly composed of a frame, a suspension mechanism, a single cultivator and a hydraulic folding mechanism. The cultivation unit includes a connecting plate, a connecting rod, a depth-limiting wheel, an S-shaped vibrating spring tooth, a small moldboard, a disc angle adjustment handle, a soil-cultivating disc, a disc height adjustment part, and a depth adjustment part of depth-limiting wheel.

The whole machine includes 5 single cultivators, which can perform up to 4-ridge operation at the same time. The single cultivator is clamped to the frame beam through U-shaped clips *(Sun, 2021; Yi et al., 2020)*. Each single cultivator is equipped with three S-shaped vibrating spring teeth, one in rows, and one on each side of the ridge wall. According to different ridge spacing requirements, the adjustment range of the distance between single cultivators is set to 700 – 900 mm to adapt to different ridge shapes and improve the universality of machines and tools. Its structure is shown in Fig. 1. Currently, most potato planting modes in China is ridge planting, which is divided into single-ridge and single-row, single-ridge and double-row. Most potato plantings in Heilongjiang Province are single-ridge and double-row, whose ridge spacing is about 90 cm. This single cultivator meets the requirements of potato cultivation in Heilongjiang Province.

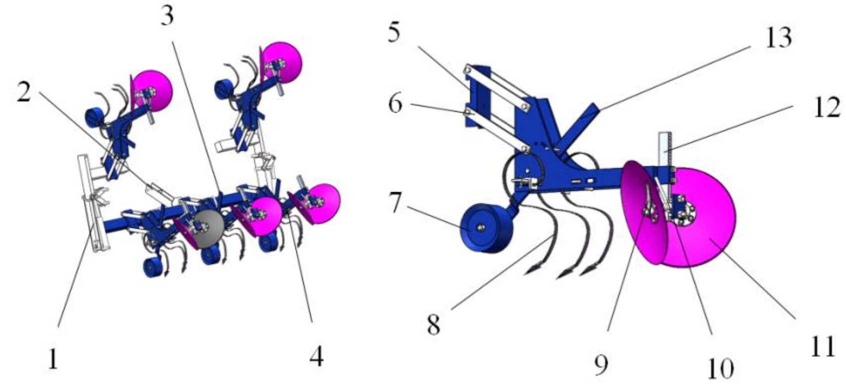


Fig. 1 - Schematic diagram of disc potato cultivator

1. Hydraulic folding mechanism; 2. Suspension mechanism; 3. Frame; 4. Single cultivator; 5. Connection board; 6. Connection bar; 7. Depth limiting wheel; 8. S-shaped vibrating spring tooth; 9. Small plow wall; 10. Disc angle adjustment handle; 11. Soil-cultivating disc; 12. Adjusting component of disc height; 13. Adjusting component of depth-limiting wheel

During the operation, the soil-cultivating disc rotates, and the direction is the same as the forward direction of the soil-cultivating disc *(Ovchinnikov et al., 2019)*. The soil-cultivating disc performs linear motion and circular motion during the movement. Let the angle of the disc relative to the horizontal plane be β and to the vertical plane be α, and β and α are the inclination angle and declination angle of the soil-cultivating disc. Respectively, the geometrical position of the soil-cultivating disc in space is shown in Fig. 2. V is the vertical plane; H is the horizontal plane, and the positive direction of x is the forward direction of the cultivator. The movement mode of the soil-cultivating disc is compound motion, including rotational motion and linear motion.

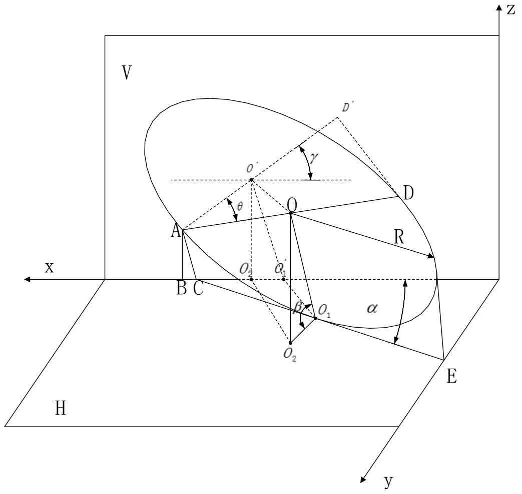


Fig. 2 - Three-dimensional coordinate system diagram of the soil-cultivating disc

When α=0 and β=0, the cultivating disc only has the function of rolling and cutting. The projection of surface H is an approximate semi-arc, and that of surface V is a circle.

The origin of the coordinate axis is set as the center of the soil-cultivating disc, and the coordinates of any point on the edge of the soil-cultivating disc as (*x,y,z*) on the XOZ projection plane.

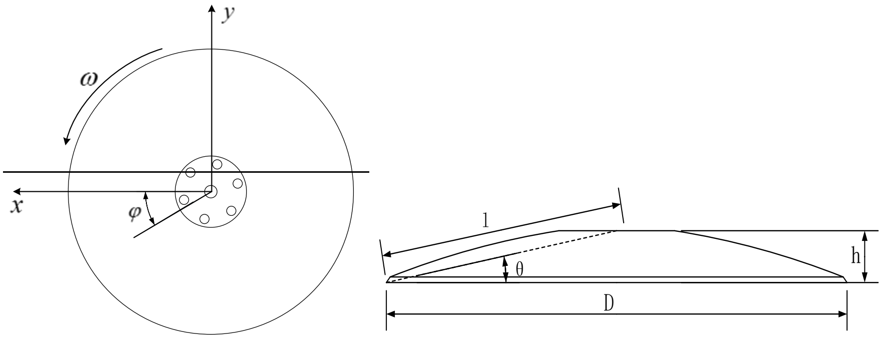


Fig. 3 - Disc structure diagram

From Fig.3, it is obtained that:

$$D = 2R \tag{1}$$

$$l = \frac{R}{\cos\theta} \tag{2}$$

$$h = l \cdot \sin\theta \tag{3}$$

where D is the diameter of the soil-cultivating disc, mm

R– radius of the soil-cultivating disc, mm

h - height of the soil-cultivating disc, mm

l - the straight-line distance between the edge of the soil-cultivating disc and the installation center of the disc, mm

The angle turned during time t is:

$$\varphi = \omega t$$

Its equation of motion can be expressed as:

$$\begin{cases} x = v_m t + R\cos\varphi \\ y = l\sin\theta \\ z = R - R\sin\varphi \end{cases} \tag{4}$$

Where t is the time of the component rotating φ , s

v_m - forward speed of the cultivator, km.h^{-1}

φ - the angle the disc has turned, (°)

ω - angular velocity of disk rotation, rad. s^{-1}

When $\alpha = 0, \beta \in (0, \frac{\pi}{2})$, the cultivating disc only has an inclination angle, but no deflection angle. At this time, it can roll and cut the soil but cannot push the soil sideways.

Taking the origin of the coordinate axis as the center of the soil-cultivating disc and the YOZ plane as the projection plane, the coordinates of any point on the edge of the soil-cultivating disc are set as (*x, y, z*), as shown in Fig. 4.

Its equation of motion can be expressed as:

$$\begin{cases} x = v_m t + R\cos\varphi \\ \begin{cases} y = l\sin(\theta+\beta) - \frac{\varphi}{\pi}2R\sin\beta (0 < \varphi \le \pi) \\ y = \frac{\varphi}{2\pi}2R\sin\beta - [2R\sin\beta - l\sin(\theta+\beta)] (\pi < \varphi \le 2\pi) \end{cases} \\ z = l\cos(\theta+\beta) - R\sin\varphi\cos\beta \end{cases} \tag{5}$$

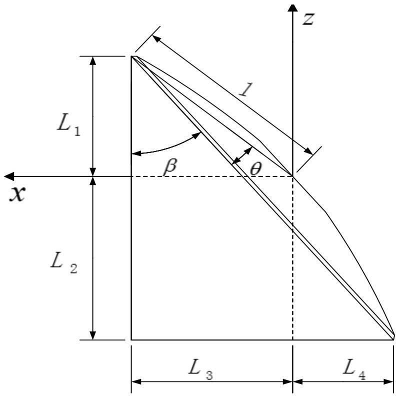


Fig. 4 - Motion diagram of the oblique disc

When $\alpha \in (0, \frac{\pi}{2}), \beta = 0$ the soil-cultivating disc only has a declination angle but no inclination angle, and it can roll and cut the soil and push the soil sideways.

Taking the origin of the coordinate axis as the center of the soil-cultivating disc, and *xoy* plane as the projection plane, the coordinates of any point on the edge of the soil-cultivating disc are set as (x, y, z), as shown in Fig. 5.

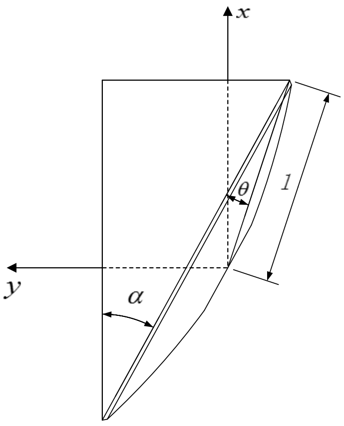


Fig. 5 - Motion diagram of the deflection disc

Its equation of motion can be expressed as

$$\begin{cases} \begin{cases} x = l\cos(\alpha-\theta) - \dfrac{\varphi}{\pi}2R\cos\alpha(0<\varphi\le\pi) \\ x = \dfrac{\varphi}{2\pi}2R\cos\alpha - [2R\cos\alpha - l\cos(\alpha-\theta)](\pi<\varphi\le 2\pi) \end{cases} \\ \begin{cases} y = \dfrac{\varphi}{\pi}2R\sin\alpha - l\sin(\alpha-\theta)(0<\varphi\le\pi) \\ y = 2R\sin\alpha - l\sin(\alpha-\theta) - \dfrac{\varphi}{\pi}2R\sin\alpha(\pi<\varphi\le 2\pi) \end{cases} \\ z = R - R\sin\varphi \end{cases} \tag{6}$$

The edge end point of the soil-cultivating disc can be obtained through the derivation of Eq. 4.

$$\begin{cases} v_x = \dfrac{dx}{dt} = \mathrm{v}_m - R\omega sin\omega t \\ v_z = \dfrac{dz}{dt} = -R\omega cos\omega t \end{cases} \tag{7}$$

The absolute velocity of the edge end point is

$$v_a = \sqrt{v_x^2 + v_z^2} \quad = v_m\sqrt{(\varepsilon)^2 - 2\varepsilon sin\varphi + 1} \tag{8}$$

Where v_a - the absolute velocity of the edge end point, m.s^{-1}

Let $\varepsilon = {}^{\omega R}\!/_{v_m}$, the speed of point on the cultivating disc is related to the speed of the implement and the position of soil-cultivating disc. With the increase of the inclination angle, the volume of cultivated soil increases and the speed of soil-cultivating disc decreases. With the increase of the inclination angle, the turning effect of the soil-cultivation disc increases.

Soil cultivation is to transfer the soil at the base of the ridge to the base of the potato plant, which plays the role of loosening the soil and thickening the soil layer, forming a dark environment suitable for the growth of underground crops, and creating conditions for multiple tubers. At the same time, after the soil cultivation, the formed potato pieces can be prevented from being exposed to the sun and be green to improve the quality of potatoes. Under the background of potato cultivation mode with large ridges, when the soil-cultivating discs operate between the ridges, the parameters of the soil-cultivating discs are provided for reference according to the effect of the soil-cultivating discs in agronomic terms.

The working state of soil-cultivating disc in ridge field is shown in Fig.6. Point O is the center of the soil-cultivating disc, and point C is the tangent point of the soil-cultivating disc at this moment and the tillage depth. During the movement of the cultivating disc from point C to point A, although some soil is thrown out, none of them could reach the highest point. AOC is at an angle of 90 degrees, and the height of the soil thrown can reach the highest level at this time.

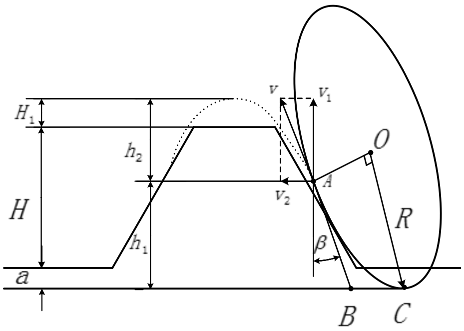


Fig. 6 - Working state of the disc

The throwing speed is as follows:

$$v = v_m cos\alpha \tag{9}$$

Where v - the throwing speed, m.s^{-1}

The maximum height that continues to rise after throwing is:

$$h_2 = \frac{v_1^2}{2g} \tag{10}$$

Where $v_1 = v\cos\beta$

Where v_1- the throwing speed, m.s^{-1}

h_2- the maximum height to rise after throwing, mm

g- the gravitational acceleration, m.s^{-2}

The distance between the soil throwing point and the tillage depth is:

$$h_1 = R\cos\beta \tag{11}$$

The height of cultivation comprehensively obtained from E $H_1 = h_1 + h_2 - a - H$ q.9 to Eq.11 is:

$$H_1 = h_1 + h_2 - a - H \tag{12}$$

Where a - the tillage depth, m

H- the ridge height, mm

H_1 -the height of cultivation, m

The final solution is as follows:

$$H_1 = \frac{D\cos\beta}{2} + \frac{(v_m\cos\alpha)^2}{2g} - \frac{D}{k} - H \tag{13}$$

Where $D = k \cdot a$

k - the coefficient between the tillage depth and disc diameter

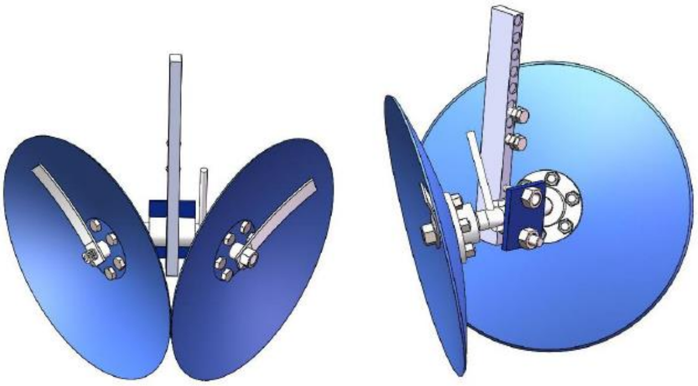
According to the agronomic requirements for soil cultivation:

$$5\text{cm} \le H_1 \le 10cm \tag{14}$$

From Eq. 13 and Eq. 14, the main factors affecting the cultivating height are the tillage depth, cultivator speed, and the inclination and declination angles of the soil-cultivating disc. The tillage depth of the disc potato cultivator is within 0.06-0.15 m. As the forward speed of the cultivator increases, the distance at which the soil-cultivating disc throws the soil increases sharply, therefore the forward speed should not exceed 7 km/h. The angle γ is adjusted through the disc angle adjustment component, and the adjustment range is within 20°-60° range. During the operation, the soil is brought to the ridge through the spiral motion of soil-cultivating disc.

The greater the energy carried by the soil, the more likely it is to damage the seedlings. The energy carried by the soil is mainly related to the tillage depth, the cultivator speed and the working angle of the cultivating disc. The greater the cultivator speed, the greater the speed of the soil thrown by the soil-cultivation disc, and the greater the energy it carries. The greater the tillage depth, the more soil the soil-cultivating disc throws out per unit time. The working angle of the soil-cultivating disc affects the height of the soil thrown by the soil-cultivating disc. The higher the height, the more energy the soil carries. At the same time, the inclined soil-cultivating disc has the effect of scraping and weeding the potato ridge during the motion. Within a certain range, the larger the angle of the soil-cultivating disc relative to the ridge side, the more obvious the weeding effect.

The model of soil-cultivating disc device is created by the three-dimensional software SolidWorks 2020, as shown in Fig. 7. At the time of creation, the coordinate axis position has been adjusted accordingly, and then the model is exported to a common format in the software. This article exported it as an .x_t format file. The general format (stp, x_t) file exported by SolidWorks 2020 software through import in the Geometry module of the EDEM software. In the whole assembly of soil-cultivating disc, the parts such as bolts and nuts are simplified, and then the simplified model is imported into the discrete element software (*Gowripathirao et al., 2019; Tekeste et al., 2019; Selech et al., 2019*).



(a)Main view (b) Axonometric drawing

Fig. 7 - Model diagram of disc soil cultivation device

The used version of discrete element simulation software is EDEM 2020. The solid model is imported into the software for EDEM simulation test. Before the test, relevant simulation parameters are set as shown in Table 1.

Table 1

Simulation parameters

Parameters	Value
Poisson's ratio of sandy loam	0.35
Soil density of sandy loam / kg/m^3	2550
Shear modulus of sandy loam / MPa	1
Static friction coefficient of sandy loam	0.541
Dynamic friction coefficient of sandy loam	0.31
Coefficient of restitution of sandy loam	0.6
Soil surface energy of sandy loam / J/mm^2	40
Soil normal stiffness per unit area of sandy loam / N/m^3	1e9
Tangential stiffness of soil per unit area of sandy loam / N/m^3	5e8
Porosity of sandy soil /%	53.8
Poisson rate of disc	0.3
Disc density / kg/m^3	7850
Disc shear modulus / MPa	7.9e4
Static friction coefficient of disc sandy loam	0.5
Dynamic friction coefficient of disc sandy loam	0.005
Coefficient of restitution of Disk - sandy loam	0.6

The Edinburgh Elasto-Plastic Adhesion (EEPA) model is selected as the parametric model between soil particles, because this elastic-plastic attachment model can better reflect the soil stress-strain *(Makange et al., 2020)*. During the simulation, the soil ridge model is established by the particle bed filling method. The position and parameters of the component model are adjusted in the 3D software, and then imported into the simulation software. The simulation process is shown in Fig. 8.

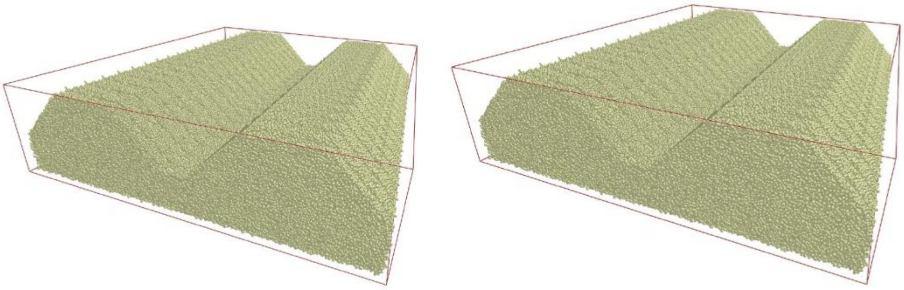

(a) Filling diagram of soil ridge (b) Simulation model diagram

Fig. 8 - Simulation operation model

(1) Parameter determination of tillage depth

The base of tillage depth is 10.5 cm. In this paper, 60, 105, and 150 mm are selected as test variables, and the other two variables are reference variables, namely 5.5 km/h and 475 mm.

(2) Parameter determination of cultivator forward speed

The reference speed of the forward speed is 5.5 km/h. In this paper, 4, 5.5, and 7 km/h are selected as the test variables, and the other two variables are the reference variables, namely 105 mm and 475 mm.

(3) Parameter determination of disc diameter

The reference value of the disc diameter is 475 mm. In this paper, 450, 475 and 600 mm are selected as the test variables, and the other two variables are the reference variables, namely 105 mm and 5.5 km/h.

The test was carried out in the experimental demonstration base of Northeast Agricultural University in Harbin, Heilongjiang Province. The soil of this demonstration base is sandy loam for dry farming. The length and width of the experimental plot were selected as 500m×400m, and the soil firmness was 892 KPa. During the experiment, potato seedlings were grown on the plot, with a height of 150-200 mm and a planting density of 7 plants/m^2.

According to the indexes of JB/T7864-1999 "Test Method for cultivator fertilizer", the soil-cultivating height was selected as the test index. According to the test code table, the test factors of each combination were changed, and three-factor and three-level orthogonal test was carried out in the test demonstration base.

Taking the forward speed, tillage depth and disc diameter of the cultivator as the test factors, and the cultivating height as the test index, a three-factor and three-level orthogonal experiment was carried out to evaluate the cultivation effect of the key components of the disc potato cultivator. It can be seen from the pre-test that if one of the three factors is changed, the remaining factors change non-linearly. Thereby, there is an interaction among the three factors. Interactions were considered as the influencing factors and were involved in the intuitive analysis of the results. Therefore, this paper uses the $L_{27}(3^{13})$ orthogonal test table to carry out 27 tests, so as to obtain the cultivating height under different conditions, calculate the range, and determine the primary and secondary influencing factors.

Through consultation and combining with the manual on farming and soil-cultivation, the soil-cultivating disc is suitable for shallow cultivating and soil loosening. According to the tillage depth, the disc diameter was calculated to be in 400 mm-450 mm, and the reference depth of the tillage depth was 10.5 cm. According to the characteristics of disc ploughing, the reference speed of the cultivator forward speed was 5.5 km/h, and the general speed should be less than 7 km/h. The specific test factor level coding table is shown in Table 2.

Table 2

Factor level coding table

Level	Factors		
	Tillage depth (mm)	Operation speed (km/h)	Disc diameter (mm)
1	60	4	450
2	105	5.5	475
3	150	7	500

RESULTS

The red in Fig. 9 is the curve between the cultivator forward speed and the particles on the ridge. In Test No. 1-3, the particles increase in turn, while in test No. 3-5, they decrease gradually. It can be seen that the particles on the ridge first increase with the increase of cultivator forward speed under the condition that other factors remain constant. After reaching a certain number, the effect of cultivator forward speed on the particles is counteracting, and the particles on the ridge decrease with the increase of cultivator forward speed.

The green in Fig. 9 is the curve between the disc diameter and the particles on the ridge. In test No. 1-5, the particles on the ridge are positively correlated with the tillage depth. It can be seen that the particles on the ridge increase with the increase of the tillage depth of the vehicle under the condition that other factors remain constant. The effect of disc diameter on the particles continues to be a positive effect.

The blue in Fig. 9 is the curve between the tillage depth and particles on the ridge. In test No.1-5, the particles increase slowly, while in test No. 3-5, they increase rapidly. It can be seen that the particles on the ridge increase with the increase of tillage depth under the condition that other factors remain constant, and the acceleration also increases.

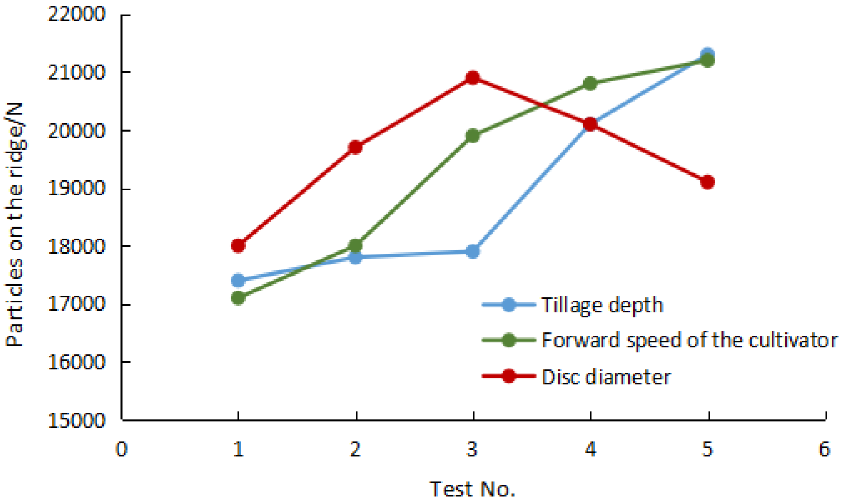


Fig. 9 - Single factor test simulation results

The range reflects the obvious degree of variation of the factor level within the test range. The larger the range value, the greater the influence of the level on the test results. It can be seen from Table 3 that the range factor A has the largest range value (62.7), and the range values of the other factors rank from large to small being C, B, (A×C)1, (B×C)1 as 60, 20, 14.3, 14, respectively. Since the range of other items is too small, it is ignored. The test shows that the tillage depth, disc diameter and operating speed (A, B, C) have a great influence on the cultivating height. The interaction of tillage depth and disc diameter, operating speed and disc diameter also had an effect on the performance index of cultivating height, but it was inferior to the effect of a single factor on it. From Table 6, with the increase of tillage depth and disc diameter, the cultivating height increases, and with the increase of random vehicle speed, the cultivating height decreases. Since the tillage depth and disc diameter have an effect on the weeding qualification rate and the seedling damage rate *(Sun, 2021)*, if tillage depth is too deep and the disc diameter is too large, the seedling damage rate would be high. On the contrary, the qualified rate of weeding would be low. Too fast or too slow operating speed would directly affect the efficiency of weeding. Therefore, the optimal scheme is $A_2B_2C_2$, and the cultivating height is 65 mm under this condition.

The primary and secondary influencing factors can be determined through the range analysis of the test data, and the significance of the influence of the factors on the test results can be obtained through the variance of the test data. In this paper, SPSS (Statistical Package for the Social Sciences) data processing software is used to analyze the variance of the qualified rate. The Sig. of factors A, B, and C is less than 0.01, which has a very significant impact on the cultivating height. The Sig. of (A×C)1 and (B×C)1 is less than 0.05 and greater than 0.01, which has a significant impact on the cultivating height. The Sig. of other factors is greater than 0.05 and has no effect on the cultivating height.

Table 3

Property index and natural variable coding table

Test No.	A	B	$(A\times B)_1$	$(A\times B)_2$	C	$(A\times C)_1$	$(A\times C)_2$	$(B\times C)_1$	9	10	$(B\times C)_2$	12	13	Cultivating height /mm
1	1	1	1	1	1	1	1	1	1	1	1	1	1	55
2	1	1	1	1	2	2	2	2	2	2	2	2	2	65
3	1	1	1	1	3	3	3	3	3	3	3	3	3	75
4	1	2	2	2	1	1	1	2	2	2	3	3	3	50
5	1	2	2	2	2	2	2	3	3	3	1	1	1	62
6	1	2	2	2	3	3	3	1	1	1	2	2	2	80
7	1	3	3	3	1	1	1	3	3	3	2	2	2	55
8	1	3	3	3	2	2	2	1	1	1	3	3	3	60
9	1	3	3	3	3	3	3	2	2	2	1	1	1	80
10	2	1	2	3	1	2	3	1	2	3	1	2	3	65
11	2	1	2	3	2	3	1	2	3	1	2	3	1	75
12	2	1	2	3	3	1	2	3	1	2	3	1	2	80
13	2	2	3	1	1	2	3	2	3	1	3	1	2	55
14	2	2	3	1	2	3	1	3	1	2	1	2	3	70
15	2	2	3	1	3	1	2	1	2	3	2	3	1	80
16	2	3	1	2	1	2	3	3	1	2	2	3	1	55
17	2	3	1	2	2	3	1	1	2	3	3	1	2	65
18	2	3	1	2	3	1	2	2	3	1	1	2	3	80
19	3	1	3	2	1	3	2	1	3	2	1	3	2	95
20	3	1	3	2	2	1	3	2	1	3	2	1	3	90
21	3	1	3	2	3	2	1	3	2	1	3	2	1	95
22	3	2	1	3	1	3	2	2	1	3	3	2	1	75
23	3	2	1	3	2	1	3	3	2	1	1	3	2	80
24	3	2	1	3	3	2	1	1	3	2	2	1	3	95
25	3	3	2	1	1	3	2	3	2	1	2	1	3	70
26	3	3	2	1	2	1	3	1	3	2	3	2	1	80
27	3	3	2	1	3	2	1	2	1	3	1	3	2	90
K_1	582	695	645	640	575	650	650	675	655	650	677	652	657	
K_2	625	647	652	672	647	642	667	660	650	670	665	665	665	
K_3	770	635	680	665	755	685	660	642	672	657	635	660	655	
k_1	194.0	231.7	215.0	213.3	191.7	216.7	216.7	225.0	218.3	216.7	225.7	217.3	219.0	
k_2	208.3	215.7	217.3	224.0	215.7	214.0	222.3	220.0	216.7	223.3	221.7	221.7	221.7	
k_3	256.7	211.7	226.7	221.7	251.7	228.3	220.0	214.0	224.0	219.0	211.7	220.0	218.3	
Range R	62.7	20.0	11.7	10.7	60.0	14.3	5.7	11.0	7.3	6.7	14.0	4.3	3.3	
Factor primary and secondary	A C B $(A\times C)_1(B\times C)_1$													
Optimal scheme	$A_2B_2C_2$													

Note: Ki is the sum of level i(i=1,2,3) in column j of the orthogonal test; k_i is the ratio of K_i to the number of horizontal occurrences; R (range) is the difference between max{K1,K2,K3} and min{K1K2K3}. A is the tillage depth; B is the operating speed; C is the disc diameter; A×B is the interaction term between wind depth and working speed; A×C is the interaction item between the wind speed and the disc, and B×C is the interaction term between the operating speed and disc diameter.

According to the results of the range and variance analysis of the orthogonal test *(Laryushin et al., 2020)*, when the tillage depth was 105 mm, the operation speed was 5.5 km/h and the disc diameter was 475 mm, the parameter combinations was optimal for soil-cultivating disc operation. In order to verify the accuracy of the optimal parameter combination, the tillage depth was set to 105 mm; the operating speed was set to 5.5 km/h, and the disc diameter was selected to be 475 mm for verification. The test was repeated three times, and the average value was calculated as the final result. The test results are shown in Table 4.

Table 4

Test verification results

Test Times	**Soil-cultivating height / mm**
1	65
2	68
3	64
Mean value	65.6

CONCLUSIONS

(1) A 90 cm potato cultivator furrow was generated by the discrete element simulation software. Taking the tillage depth, forward speed, and disc diameter of the cultivator as test factors, and the cultivating height as test index, a single-factor simulation test was carried out. The results show that the forward speed increases first and then decreases with the particles on the ridge. The disc diameter increases with the particles on the ridge, and the change is obvious. The tillage depth also increases with the increase of the particles on the ridge, and the increasing range gradually increases.

(2) Through the orthogonal test of three-factor and three-level in the demonstration base, it is obtained that when the tillage depth was 105 mm, the operation speed was 5.5 km/h, and the disc diameter was 475 mm, the effect of soil-cultivating disc was optimal, which is about 65 mm. The test was repeated for 3 times to verify the optimal combination. The results were basically consistent with those of the field test, so that the test results were reliable.

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REFERENCES

[1] Gowripathirao, N. R. N. V., Chaudhary, H., Sharma, A. K. (2019). Design and development of vibratory cultivator using optimization algorithms. *SN Appl. Sci*. Vol. 1, no.10, ISSN 2523-3963, pp. 1-17, Switzerland.

[2] Hwang, S.J., Jang, M.-K., Nam, J.-S. (2021). Application of Lateral Overturning and Backward Rollover Analysis in a Multi-Purpose Agricultural Machine Developed in South Korea. *Agronomy,* Vol. 11, 297, ISSN 2073-4395, Switzerland.

[3] Kroupin, P. Y., Semenov, O. G. *(*2018). Physical Methods of Pre-planning and Postharvest Treatment of Potato: A Review. *RUDN Journal of Agronomy and Animal Industries*, Vol. 13, no.4, ISSN 2312-797X, pp. 383-395, Russia.

[4] Laryushin, N. P., Kukharev, O. N., Bochkarev, A. S., Bochkarev, V. S. (2020). Laboratory field studies of mini potato planter. *BIO Web of Conferences,* 17, 1-5, E-ISSN 2117-4458, France.

[5] Liu. J. (2011). Research Status and Prospects of Potato Industry in China (我国马铃薯产业技术研究现状及展望). *Journal of Agricultural Science and Technology,* Vol. 13, no.05, pp. 13-18, Beijing / China.

[6] Lv, J. Q., Shang, Q. Q., Yang, Y., Wang, Y. B., Li, Z. H. (2017). Design and Experiment Analysis of 1ZL5 Type Cultivator. *Journal of Agricultural Mechanization Research*, Vol. 39, no.02, ISSN 1003-188X, pp. 79-83, USA.

[7] Lv, J. Q., Tian, Z. E., Yang, Y., Shang, Q. Q., Wu J. E., Li, Z. H., Wang, X. Y. (2015). The Development Situation, Existing Problems and Development Trend of Potato Machinery (马铃薯机械发展现状、存在问题及发展趋势). *Journal of Agricultural Mechanization Research,* Vol. 37, no.12, ISSN 1003-188X, pp. 258-263, Heilongjiang/China.

[8] *Makange, N. R.,* Ji, C. Y., Torotwa, I. (2020). Prediction of cutting forces and soil behavior with discrete element simulation. *Computers and Electronics in Agriculture*, 179. S. 105848, ISSN 0168-1699, England.

[9] Ovchinnikov, S., Bocharnikov, V. S., Vorob'yeva, N. S., Ivanov, A. G. (2019). Kinematic study of the weeding robot. *IOP Conference Series: Materials Science and Engineering,* Vol. 489, no.1, ISSN 17578981, England.

[10] Qiu,T.Y., Wang, L. L., Chen, W. P., Zhang, B. C., Yang, S. D. (2020). Research status and prospects of potato seed-metering device. *American Journal of Agricultural Research*, (5), 101,ISSN 0002-9092, USA.

[11] Ribeiro, P., Faroni, L., Heleno, F., Queiroz, M., Prates, L. (2020). Determination of the Pesticides in Water Used in the Culture and Processing of Potatoes. *Química Nova,* Vol. 43, no.8, ISSN 0100-4042, pp. 1026-1034, Brazil.

[12] Selech, J., Ulbrich, D., Kęska, W., Staszak, Ż. K., Marcinkiewicz, J., Romek, D., Rogoziński, P. *(2019).* Design of a cultivator mounted on a tractor with a power of up to 20 kW. *MATEC Web of Conferences,* 254, 05003, E-ISSN 2261-236X, France.

[13] Sun, Z. J. (2021). Design and experimental research on disc potato cultivator (圆盘式马铃薯栽培机的设计与试验研究). Master dissertation, *Heilongjiang Bayi Agricultural University*, Heilongjiang/China.

[14] Tang, P., Ren, S. Y., A, J. K., Liu, Z., Lv, X. R. (2021). Design of a potato stubble cutting machine for side delivery. Proceedings of 2021 International Conference on Advanced Energy. *Power and Electrical Engineering*, pp. 430-434, Shaanxi/China.

[15] Tekeste, M. Z., Balvanz, L. R., Hatfield, J. L., Ghorbani. S. (2019). Discrete element modeling of cultivator sweep-to-soil interaction: Worn and hardened edges effects on soil-tool forces and soil flow. *Journal of Terramechanics,* Vol. 82, ISSN 0022-4898, pp. 1-11, England.

[16] Yi, S. J., Sun, Z. J., Li, Y. F., Li, Z. H., Li, J. C., Lv, J. Q. (2020). Design and Test of Disc Potato Cultivator at Early Inter-tillage (马铃薯中耕前期圆盘式中耕机设计与试验), *Transactions of the Chinese Society for Agricultural Machinery,* Vol. 51, no.08, ISSN1000-1298, pp. 98-108, Beijing/China.

[17] Zheng, Z. Q., Zhao, H. B., Liu, Z. D., He, J., Liu, W. Z. (2021). Research Progress and Development of Mechanized Potato Planters: A Review. *Agriculture,* Vol. 11, no.6, 521, ISSN 0551-3677, Switzerland.