Design and experiment of the ditching device with combined rotary tillage and chisel shovel for lateral deep fertilization in tea garden

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Abstract: To solve the difficulty in ditching for the deep fertilization in tea gardens caused by the high quantity of tea branches and stubbles, a new ditching device combined with a kind of rotary tillage and chisel shovel was designed. The combined ditching device worked by the following steps: Firstly, the stubble, such as fallen leaves and weeds between the rows, was cleaned up and thrown away by the rotary tillage. Then, the chisel-shaped fertilizing shovel forcefully dug into the soil, realizing the deep fertilization groove. The parameters of the rotary tillage and stubble-throwing device and the chisel-shaped fertilizing shovel were optimized by single factor test and quadratic regression orthogonal rotation test, respectively. The optimization results showed that when the number of stubble-throwing blades of the rotary tillage and stubble-throwing device was five, and the blade installation inclination angle was 16°, the stubble removal rate was the highest at the high speed of the cutter (300 r/min), which was 91.64%. When the entry angle of the chisel-shaped fertilizing shovel was 30°, the entry clearance angle was 8°, and the operating speed was 0.7 m/s, the stability coefficient of the groove depth was 94.9%, which was the optimal parameter of the chisel-shaped fertilizing shovel. The field experiment showed that the average width of the ditching was 224 mm (between 202-248 mm), the average depth of the groove was 194.9 mm (between 173-218 mm), and the stability coefficient of the groove depth could reach 92.78%, realizing stable lateral deep fertilization in the tea garden.

Keywords: tea garden, rotary tillage and stubble throwing, chisel shovel fertilizer, combined ditching, parameters optimization
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1 Introduction

Tea trees have been planted in China for more than 3000 years. From 2010 to 2020, the average annual tea planting area in China was 2.73 million hm^2, and the tea production was 2.219 million tons. The total tea planting area and tea production in China are both first in the world[1-3]. Nearly 60% of tea plantations in China are planted in hilly areas with rugged terrain and poor soil. Fertilization can increase the yield of tea by more than 40%, which is the main measure to ensure the yield and quality of tea[4-6]. The root system of tea tree is abundant and developed. The main roots can penetrate vertically into the soil layer by 2-3 m, lateral roots are mostly distributed in the soil layer of 20-50 cm, and absorption roots are distributed in the soil layer of 20-30 cm underground. Deep application of fertilizer is conducive to the absorption of nutrients by tea tree roots, improving the utilization rate of fertilizer and reducing environmental pollution[7-10]. It is therefore of great economic significance and ecological benefit to implement lateral deep fertilization in tea garden soil above 20 cm.

Tea is a perennial evergreen shrub. As time goes by, the amount of leaves, tea branches, and weeds covered between the rows of tea trees is very large, which can reach 2.18-3.68 kg/m^2, resulting in difficulty getting into the soil and easy jamming for traditional trencher. The hoe shovel trencher, wing shovel trencher, core share trencher, boat shovel trencher, boot-shoe type trencher, sliding blade type trencher, double-disc type trencher, and single-disc type trencher that are usually used in field[11,12] all experience difficulty in digging deep in the tea garden. Digging deep trenches under high stubble cover is one of the key problems of deep fertilization in tea gardens.

In order to realize surface trenching under high stubble cover, domestic and foreign scholars mostly adopt the method of clearing stubble before trenching to reduce the congestion of trenching and realize trenching operation. Huang et al.[13] combined a concave notching disc stubble cleaner and a grass guide device to realize the cutting, shifting, and guiding of stubble. Wang et al.[14] designed a double-vane symmetrical rotary blade, which was proved to be superior to ordinary rotary tillage knives in soil loosening, weeding, and leveling through experiments. Zhao et al.[15] used a side-throwing device of no-till or minimum-till seeder for anti-blocking and seedbed-cleaning with an anti-entanglement board to coordinate with a trencher and a deflector, which not only realized the side-throwing of stubble, but also did not easily entangle, and the stubble removal rate was high. Luo et al.[16] combined the straw crushing device with the straw diversion device and designed a seeding machine for the whole straw hard crop field. Wang et al.[17] developed an active anti-blocking device that was used in combination with the no-till seeder in wheat stubble field, designed the structural parameters of the stubble clearing and covering cutter teeth, and carried out parameter optimization and field performance

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tests. Wang et al.[18] designed a driving stubble cutter for corn strip, which has less tillage resistance and soil disturbance than the driven disc cutter. Huang et al.[19] designed a vertical stubble removal anti-blocking device, which can use the rotation of a vertical tool to break weeds and stalks in the seedling zone and then scatter them to both sides. Shi et al.[20] designed a device that could be used to pick up and crush straw, cover straw between rows, and remove straw from seeds. The combined trenching method, which cuts, breaks, and throws the stubble on the surface through the stubble cleaning device, and then trenches, is an effective way to achieve trenching under the condition of high stubble cover.

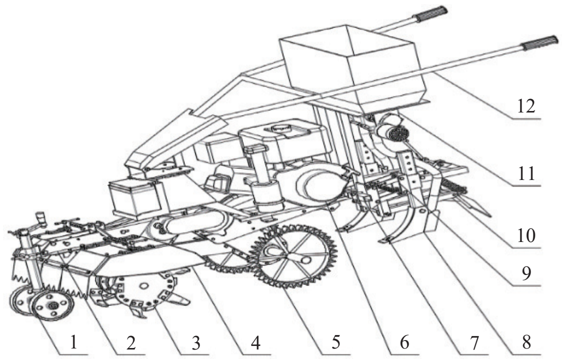
In order to realize deep trenching, domestic and foreign scholars mostly use the combination of front and rear trenching and driving double disc trenching to continuously improve the depth of trenching. Zhao et al.[21] adopted the combination of self-positioning stubble-breaking disc cutter and arc fertilization shovel to design deep layer fertilization and sowing on the side of no-tillage seeder, and the fertilization depth could reach 150 mm. Zhao et al.[22] designed a segmented maize sowing trencher with a sowing depth of 180 mm based on the principle of breaking stubble blade and fertilizing shovel trenching. Liao et al.[23] designed a combined ship-type trencher, which combined with a front-mounted mouldboard plow and was able to open a trapezoidal trench of 194.0-229.5 mm; the stability coefficients of both the width and depth of the trench reached more than 90%. Qin et al.[24] designed a combined cutting and throwing ditching blade for tea garden, which achieved a dumping width of 22.7 cm and a stable ditching depth of 20 cm, and the stability coefficient of ditching depth was 87.8%. Zhang et al.[25] designed an orchard double-row trenching applicator with automatic depth adjustment by using a driven double-disc trencher, and the fertilization depth was adjustable from 200 to 400 mm. The driving type active trenching and combination trenching are helpful to improve the trenching depth. Ma et al.[26] designed a segmented cutting trenching device, and its cutting process was simulated according to the response surface test design. Sun et al.[27] designed a novel intelligent trenching and fertilizing machine, which can implement automatic navigation and adjustable trenching depth for orchards. Ma et al.[28] designed a disc subsection cutting trenching device, and the optimization model of trenching performance quality was constructed to obtain the optimal parameter combination of influencing factors. Chen et al.[29] designed a dual-disc trenching device, and used discrete element method (DEM) to determine the impact of key structural parameters on the tillage depth stability and working resistance.

This study was carried out to solve the problem of deep fertilization and trenching in tea gardens caused by the excessive residue of deciduous tea branches on the surface. A rotary tillage and stubble-throwing device was used to clean the leaves, tea branches, and weeds between rows, and then a gouge fertilizer shovel was adopted to dig into the soil and open trenches to achieve stable and deep lateral fertilization in tea gardens. The ditch opening device of rotary tillage and stubble disposal combined with lateral deep fertilization in tea garden was designed, and the parameters of the rotary tillage and stubble disposal device and chisel fertilizer shovel were designed and optimized.

2 Structure and working principle

2.1 Structure and working principle of deep lateral fertilization machine in tea garden

As shown in Figure 1, the side deep fertilization machine in tea garden is mainly composed of a walking device, a gasoline engine, a front frame, a back frame, a rotary tillage and stubble disposal device, a chisel-shaped fertilization shovel, an opposite double helix outer groove wheel fertilizer discharge device, and a soil covering device, etc., which can realize the functions of rotary tillage, stubble disposal, ditching, fertilization, and soil covering.



1.Tillage depth adjustment device 2. Front frame 3. Rotary tillage and stubble-throwing device 4. Earth retaining plate 5. Walking device 6. Gasoline engine 7. Rear frame 8. Chisel-shaped fertilizing shovel 9. Ditching profiling mechanism 10. Soil covering device 11. Opposite double helix outer groove wheel fertilizer discharge device 12. Armrest bracket

Figure 1 Structure of side deep fertilization machine in tea garden

The rotary tillage and stubble-throwing device is installed in the front frame of the side deep fertilizer applicator with the tillage depth adjustment device, and a chisel-shaped fertilization shovel with a copying mechanism is installed on the left and right sides of the machine. An opposing double-spiral outer groove wheel fertilizer discharging device is installed above the chisel-shaped fertilization shovel, and a soil covering device is installed behind. Above the chisel-shaped fertilization shovel is a fertilizer discharge device with double spiral outer groove wheel, and the soil covering device is installed behind it. Before the operation, it is necessary to reasonably adjust the depth adjustment device and the height of the chisel fertilizer shovel according to the surface condition and fertilization requirements of the tea garden rows. The gasoline engine provides power, and the belt pulley drives the clutch when operating, driven by the belt pulley. Through the clutch, the power is passed into the traveling gearbox in one direction to drive the traveling wheel to advance the machine, and it also is passed into the rotary tillage gearbox in the other direction to drive the rotating tillage and stubble-throwing device, which can cut the grass, fallen leaves, and other stubble on the surface of the tea garden and throw it to both sides. Then the chisel-shaped fertilization shovel buries and trenches. The fertilizer is applied to the bottom of the ditch by the opposite double helix outer groove wheel fertilizer discharge device along the fertilizer discharge hose through the chisel fertilization shovel, and the soil covering device completes the soil covering.

2.2 Structure and working principle of rotary tillage and stubble disposal combined trenching device

The ditching device with combined rotary tillage and chisel shovel is composed of a rotary tillage and stubble disposal device on the front side of the machine and a chisel-shaped fertilization shovel on the back side. When operating, the rotary tillage and stubble disposal device cuts the surface stubble and shallow dry soil between rows in the tea garden and throws them to both sides, and the chisel-shaped fertilization shovel further furrows them on the basis of the device. The schematic diagram of the operation process is shown in Figure 2.

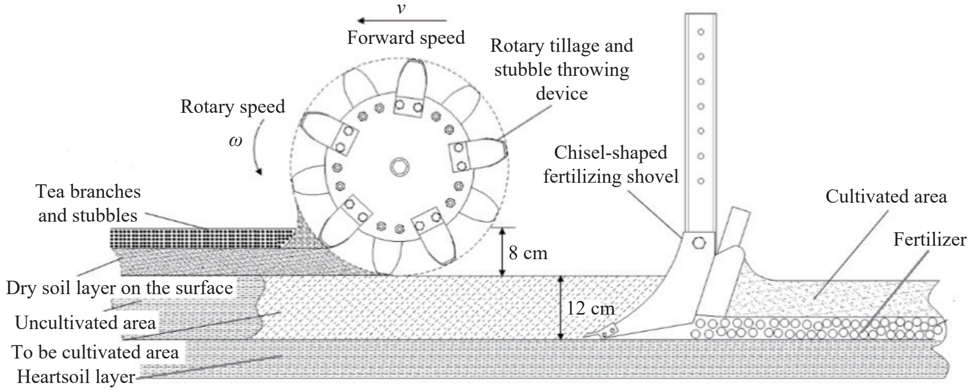


Figure 2 Schematic diagram of ditching process

In order to break the stubble and throw it to the root of the tea tree and clear the ditching belt, a rotary tillage and stubble-throwing device is designed. The ditching device consists of two inclined opposite discs with an angle of 20°. The structure of a single disc is shown in Figure 3. The stubble-throwing blade is installed on the outside of the disc at a certain angle along the radial path of the cutter near the tea tree side, and the stubble-breaking blade is installed on the inside of the disc. During operation, the stubble-breaking blade inside the cutter head can break the stubble in the rotating shaft area, and the stubble-throwing blade outside the cutter head can throw the stubble to both sides of the ditch, forming two fat trenches with a depth of 80 mm and a width of 224 mm.

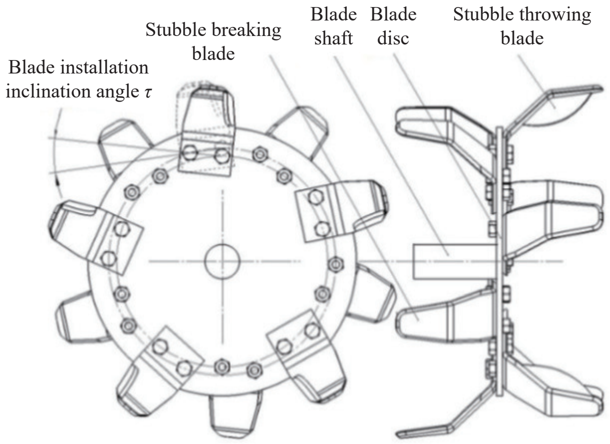


Figure 3 Schematic diagram of structure of rotary tillage and stubble-throwing device

After the operation of the rotating tillage and stubble-throwing device, the operation area of the fertilizer shovel is the trench zone with a little stubble, which requires the gouge fertilizer shovel to have narrow ditching width and strong ability to enter the soil with small soil disturbance. A chisel-shaped fertilization shovel was used to further dig the deep ditch, and its structure is shown in Figure 4.

According to the requirements of deep fertilization operation in tea garden, it is necessary to dig a 224 mm-wide and 120 mm-deep fertilizer trench in the area after the rotating tillage and stubble-throwing operation.

3 Kinematic analysis of rotary tillage and stubble disposal combined trenching device

The Cartesian coordinate system is established with the rotation center of the cutter head as the origin. The operation direction of the tool is X-axis forward, while the vertical upward direction

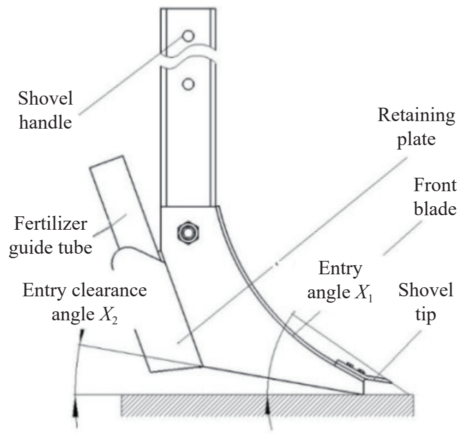


Figure 4 Overall structure of chisel-shaped fertilizing shovel

perpendicular to the ground is Z-axis forward, and the vertical direction of the X-axis in the horizontal plane is the Y-axis. The motion trajectory equation of the point on the tip of the stubble cutter is:

$$\begin{cases} x = vt + R\cos\left(\dfrac{\pi nt}{30}\right) \\ y = R\sin\left(\dfrac{\pi nt}{30}\right) \end{cases} \tag{1}$$

In order for the stubble-cutting tool to throw soil backward, the component speed of the tool tip along the X-axis needs to be backward, that is:

$$v_x = \frac{\mathrm{d}x}{\mathrm{d}y} = v - \frac{\pi nR}{30}\sin\left(\frac{\pi nt}{30}\right) < 0 \tag{2}$$

The horizontal sub-speed backward at the time of burying the blade tip is the smallest, so the speed at the time of burying needs to have a backward horizontal sub-speed, and when burying:

$$\sin\left(\frac{\pi nt}{30}\right) = \frac{R-h}{R} \tag{3}$$

It is obtained that the normal working condition of the unit is:

$$v < \frac{\pi n(R-h)}{30} \tag{4}$$

where, n is the speed of the buried roll, r/min; t is the working time of the machine, s; v is the forward speed of the tool, m/s; v_x is the horizontal sub-velocity of the tip point, m/s; R is the distance from any point on the buried roll to the axis, mm; h is tillage depth, m.

The stubble on the surface of the tea garden between rows was approximately equivalent to loose particles, and the contact point between stubble particles and stubble-throwing tools was analyzed dynamically, as shown in Figure 5.

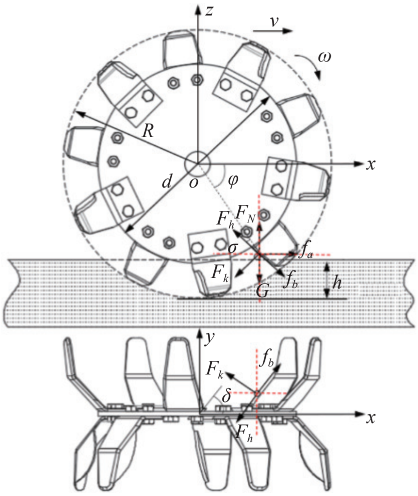


Figure 5 Fertilizer particle horizontal plane force

$$\begin{cases} f_a + f_b\cos(\varphi-\sigma)\cos\delta - F_k\sin(\varphi-\sigma)\sin\delta - \\ \quad F_h\cos(\varphi-\sigma)\cos\delta = m\dfrac{d^2x}{dt^2} \\ F_k\sin(\varphi-\sigma)\cos\delta + f_b\cos(\varphi-\sigma)\sin\delta - \\ \quad F_h\cos(\varphi-\sigma)\sin\delta = m\dfrac{d^2y}{dt^2} \\ F_N - G + F_h\sin(\varphi-\sigma) - F_k\cos(\varphi-\sigma) - \\ \quad f_b\sin(\varphi-\sigma) = m\dfrac{d^2z}{dt^2} \end{cases} \tag{5}$$

Assuming that the friction angle between the stubble particles and the surface is ρ_1, and the friction angle between the stubble particles and the rotary tillage stubble-throwing tool is ρ_2, it can be seen that:

$$\begin{cases} f_a = F_N\tan\rho_1 \\ f_b = F_N\cos\varphi\tan\rho_2 \\ F_h = F_k\tan\rho_2 \end{cases} \tag{6}$$

where, f_a is the surface friction force on stubble particles, N; f_b is the friction force of rotary tillage stubble-throwing tool on stubble particles, N; F_k is the cutting force of rotary tillage stubble-throwing tool on stubble particles, N; F_h is the sliding shear force of rotary tillage stubble-throwing tool on stubble particles, N; F'_N is surface support for stubble particles, N; G is the gravity of stubble particles themselves, N; φ is the angle between the forward direction of the tool and the center of rotation of the tool and the contact point between the blade and the stubble particle, (°); σ is the angle between the center of rotation of the tool and the contact point between the blade and the stubble particle and the sliding cutting force of the tool, (°); δ is the angle between the friction force of the rotary tillage stubble-throwing tool on stubble particles and the X-axis, (°).

The fractional velocity of stubble particles can be obtained from Equations (5) and (6), and the velocity of stubble throwing backwards and sideways must be satisfied.

$$\begin{cases} v_x = \dfrac{t}{m}[F_N\tan\rho_1 + F_k(\cos(\varphi-\sigma)\tan\rho_2\cos\delta \\ \quad -\sin(\varphi-\sigma)\sin\delta) - F_h\cos(\varphi-\sigma)\cos\delta] < 0 \\ v_y = \dfrac{t}{m}[F_k(\sin(\varphi-\sigma)\cos\delta + \cos(\varphi-\sigma)\tan\rho_2\sin\delta) \\ \quad - F_h\cos(\varphi-\sigma)\sin\delta] < 0 \\ v_z = \dfrac{t}{m}[F_h\sin(\varphi-\sigma) - F_k(\cos(\varphi-\sigma) + \sin(\varphi-\sigma)\tan\rho_2)] > 0 \end{cases} \tag{7}$$

4 Parameter optimization of rotary tillage and stubble disposal combined trenching device

4.1 Parameter optimization of rotary tillage stubble-throwing device

The stubble clearing effect of rotary tillage and stubble-throwing device has a significant influence on the trenching effect of subsequent fertilizer shovel. The single factor test method was used to study the effect of tool configuration and blade installation angle on the stubble removal rate of rotary tillage stubble disposal device under fast and slow tool speed.

4.1.1 Test factors and levels

Tool configuration: Five stubble-breaking knives are installed on the inside of the cutter head of the rotary tillage stubble-throwing device, and five blades are staggered on the outside of the cutter head. There are six kinds of tool configuration schemes on the outside of the disc: (1) Five stubble-breaking knives, no stubble-throwing knives; (2) Four stubble-breaking knives, one stubble-throwing knife; (3) Three stubble-breaking knives, two stubble-throwing knives; (4) Two stubble-breaking knives, three stubble-throwing knives; (5) One stubble-breaking blade, four stubble-throwing blades; (6) No stubble-breaking blades, five stubble-throwing blades.

Tool mounting angle: The installation angle refers to the angle between the symmetrical center of the tool and the radial installation position. Appropriately increasing the installation angle can increase the residence time of the soil residue in the bending part of the stubble-throwing tool and increase the throwing time, but too large of an angle will lead to a reduction in the operating depth of the tool. The installation angle of the blade is selected to be 0°-24°, which is divided into four levels (0°, 8°, 16°, and 24°).

Tool shaft speed: In actual work, the output cutter shaft speed is realized by the power mechanical gear switch, the corresponding speed of the fast gear is 300 r/min, and the corresponding speed of the slow gear is 220 r/ min.

4.1.2 Test conditions

The experiment was carried out in Liangzihu District of Ezhou City, Hubei Province. The tea garden is located between a high mountain and a big lake. The soil pH is suitable and the light is sufficient, which is suitable for the growth of tea trees. Before the experiment, the main characteristics of soil and the stubble cover on the surface of the tea garden were measured, and the results showed that the soil firmness of the tea garden ranged from 254.1 to 394.6 N/m^2 in the 0-30 cm soil layer, with an average value of 328.73 N/m^2. The soil moisture content ranged from 15.76% to 26.31%, with an average of 20.66%. The soil bulk density ranged from 1.32 to 1.58 g/cm^3, with an average of 1.41 g/cm^3. The average cover thickness of leaves, weeds, and other stubble on the surface was 40.78 mm, and the average cover amount was 2.83 kg/m^2.

4.1.3 Test method and measurement index

The length of the experiment was 100 m. The machine was used to fertilize the tea garden. This study removed 10 m at the head and 10 m at the end of the field, and collected data in the middle stable area. A self-made square frame (30 cm×30 cm×10 cm) was used to measure the stubble quality before and after the operation of the sampling points in the operation area of the rotary tillage and stubble-throwing device. The stubble removal rate η after the operation of the rotary tillage stubble disposal device could be calculated according to Equation (8).

$$\eta = \frac{m_q - m_h}{m_q} \times 100\% \tag{8}$$

where, η is the stubble removal rate, %; m_q is the stubble mass before operation in the sampling area, g; m_h is the residue mass after operation in the sampling area, g.

4.1.4 Analysis of test results

The test revealed the effect of different numbers of stubble blades on stubble removal rate. In the course of the test, the cutter head with the blade angle of 0° was selected to measure the actual operation effect of the rotary tillage and stubble-throwing device under the two rotating speeds of fast and slow. The relationship between the measured stubble removal rate and the number of stubble throwers is shown in Figure 6.

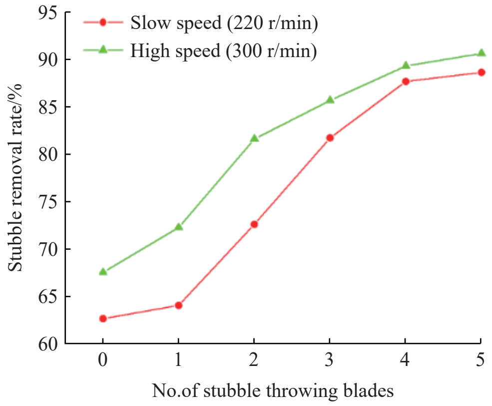


Figure 6 Effect of number of stubble-throwing knives on stubble removal rate

It can be seen from Figure 6 that with the increase of the number of stubble throwers, the stubble removal rate of the rotary tillage stubble thrower device becomes higher and higher. When the number of stubble throwers is five, the stubble removal rate is the highest, and the effect of surface stubble throwers on stubble throwers is significantly improved. It is 90.67% at the fast speed and 88.67% at the slow speed. When the number of stubble blades is fixed, the stubble removal rate is higher at the fast speed than the slow speed.

The test also measured the effect of different blade installation angles on stubble removal rate. When the number of stubble-throwing blades with the tool is five and the tool installation angle is changed, the relationship between the stubble removal rate and the blade installation angle is shown in Figure 7.

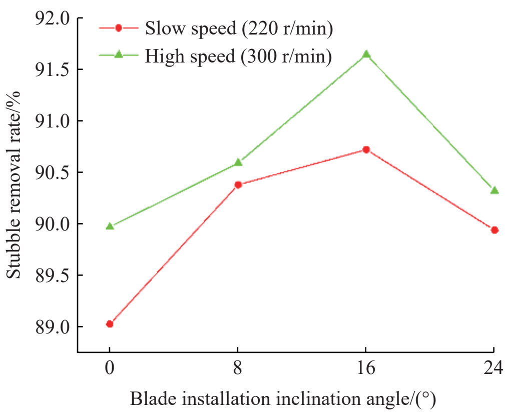


Figure 7 Influence of blade installation angle on stubble removal rate

As can be seen from Figure 7, with the increase of blade installation angle, tool stubble removal first increases and then decreases. Too large of a tool installation angle reduces the turning radius of tool tip and the line velocity of stubble throwing, resulting in a decrease in stubble removal rate. When the blade installation angle is 16°, the removal rate is the highest, 91.64% at fast speed and 90.72% at slow speed, and the removal rate at fast speed is better than that at slow speed.

4.2 Parameter optimization of chisel fertilization shovel

The entry angle refers to the angle between the action surface of the chiseled fertilizer shovel and the ground when it cuts into the soil during the process of ditching. The size of the entry angle directly determines the penetration resistance of the chisel-shaped fertilizer shovel, and the larger the entry angle, the larger the chisel-shaped fertilizer shovel. The better the soil entry effect is, the greater the entry resistance will be. Therefore, the key to reducing drag and increasing efficiency is to choose a reasonable entry angle of chisel-shaped fertilizer shovel. The results of the existing research show that the reasonable selection range of the entry angle of the fertilizer shovel is 20° to 30°.

The clearance angle refers to the angle formed between the chipped fertilizer shovel and the ground. If the clearance angle is too large, the gravity in the vertical direction of the chisel-shaped fertilization shovel will increase, and the soil will fall back, and it is difficult to ensure the consistency of the trench depth. If the clearance angle is too small, it will reduce the force of the chipped fertilizer shovel in the direction of penetration and increase the friction resistance. In order to facilitate the penetration of the chisel-shaped fertilizer shovel, it is particularly important to select a reasonable clearance angle for the chisel-shaped fertilizer shovel. Related studies have shown that the clearance angle of chisel-shaped fertilizer shovels is usually 0°-12°, and the resistance of this shovel in this range first decreases and then increases. Therefore, in order to improve the penetration ability and reduce the resistance of ditching, the range is further narrowed to 4°-8°.

The effects of entry angle, clearance angle, and machine speed on the stability of trench depth were studied by quadratic regression orthogonal test to optimize the parameters of the chisel fertilizer shovel.

4.2.1 Test factors and levels

In the same plot as the parameter optimization test of the rotary tillage and stubble-throwing device, quadratic regression general rotation orthogonal test was adopted to study the influence of the entry angle, entry clearance angle, and tool forward speed of the chisel fertilizer shovel on the stability of the ditch depth. The level coding table of the test factors is listed in Table 1.

Table 1 Test factor level coding table

Coding level	Entry angle X_1/(°)	Entry clearance angle X_2/(°)	Forward speed X_3/m·s^{-1}
–1	20	4	0.5
0	25	6	0.7
1	30	8	0.9

4.2.2 Measurement indicators and methods

After the test, a point was measured every 2 m in the working area, and a total of three points were measured to measure the width and depth of the trench bottom. The stability coefficient of ditch depth under different test conditions is calculated as follows:

$$\begin{cases} S = \sqrt{\dfrac{\sum_{i=1}^{N}(H_i - \bar{H})^2}{N-1}} \\ V = \dfrac{S}{\bar{H}} \times 100\% \\ Y = 1 - V \end{cases} \tag{9}$$

where, N is the number of measurements (N=3); H is the mean trench depth, mm; $\bar{H}=\frac{1}{N}\sum_{i}^{N}H_i$; H_i is the depth of the opening trench at the i place, mm; S is the standard deviation of trench depth, mm; V is the variation coefficient of groove depth, %; Y is the stability coefficient of ditch depth, %.

4.2.3 Analysis of test results

There are a total of 17 combinations in the test, and the experimental design and results are listed in Table 2.

Table 2 Experimental design and results

No.	Test factor			Ditch depth /mm			Coefficient of ditch depth Y/%
	X_1/(°)	X_2/(°)	X_3/m·s^{-1}	Test point 1	Test point 2	Test point 3	
1	25	4	0.9	83.7	109.4	98.3	89.2
2	25	6	0.7	92.1	89.4	106.0	92.4
3	20	8	0.7	112.7	87.5	91.7	88.7
4	25	8	0.5	109.8	98.3	80.3	87.4
5	25	6	0.7	92.2	103.9	82.3	90.5
6	25	8	0.9	77.3	92.6	103.5	88.2
7	25	6	0.7	91.2	83.7	101.3	92.2
8	25	4	0.5	84.5	114.3	93.1	87.2
9	30	8	0.7	96.0	101.3	89.4	94.9
10	30	6	0.9	105.7	87.3	91.8	91.7
11	20	6	0.9	93.1	104.9	77.2	87.6
12	20	4	0.7	74.2	96.7	103.4	86.3
13	30	4	0.7	103.9	85.9	94.2	90.2
14	25	6	0.7	85.1	104.2	92.6	91.6
15	25	6	0.7	84.1	95.5	99.8	92.9
16	20	6	0.5	80.8	93.3	116.6	84.7
17	30	6	0.5	94.3	92.1	107.1	93.2

The Design-Expert10 software was used to establish the regression model and conduct variance analysis on the above test data. The regression equation of the stability coefficient Y of the trench depth was obtained as follows:

$$Y=91.93+2.85X_1+0.77X_2+0.54X_3+0.57X_1X_2-1.11X_1X_3-0.30X_2X_3-0.28X_1^2-1.62X_2^2-2.34X_3^2$$

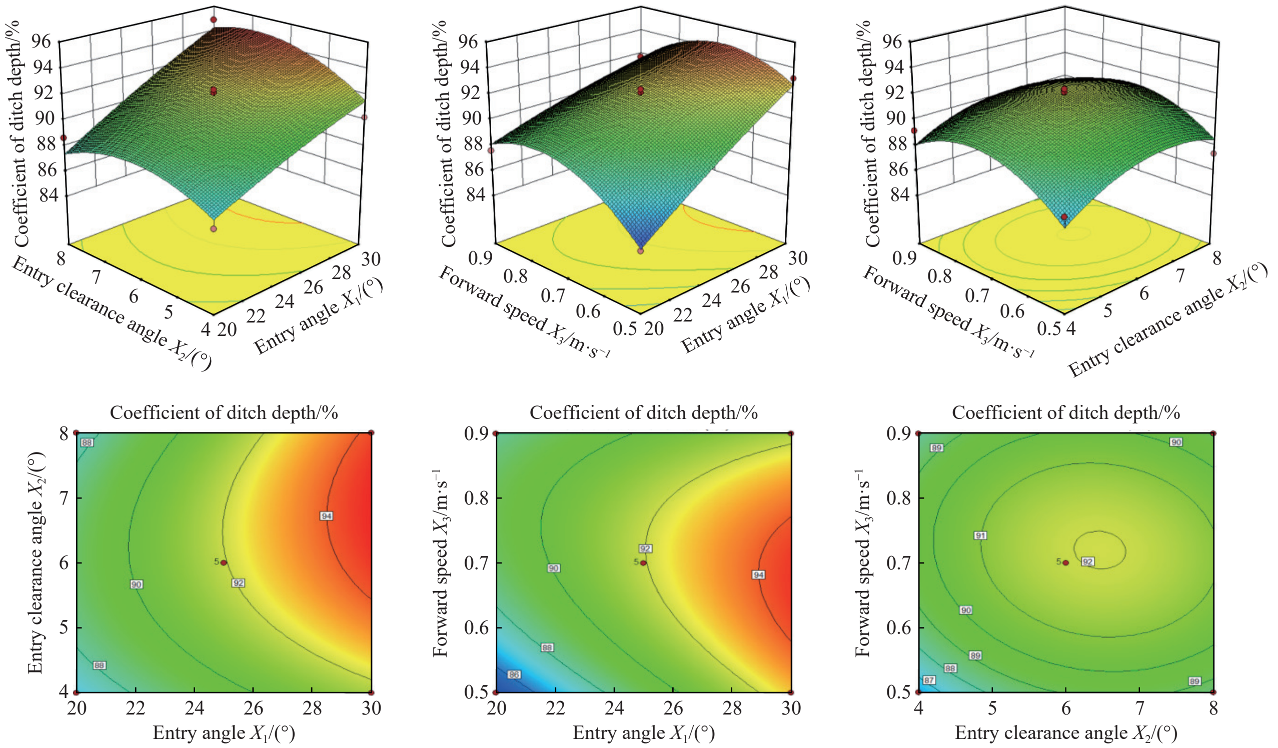
Through the variance analysis of the regression equation, Table 3 is obtained.

Table 3 Variance analysis of groove depth stability coefficient

Source of variance	Sum of square	Degrees of freedom	Mean square	F value	p-value	Significance
Model	115.46	9	12.83	8.05	0.0059	**
X_1	64.98	1	64.98	40.76	0.0004	**
X_2	4.77	1	4.77	2.99	0.1272	
X_3	2.31	1	2.31	1.45	0.2677	
X_1X_2	1.31	1	1.31	0.82	0.3946	
X_2X_3	4.95	1	4.95	3.11	0.1214	
X_1X_3	0.35	1	0.35	0.22	0.6518	
X_1^2	0.32	1	0.32	0.20	0.6676	
X_2^2	10.99	1	10.99	6.90	0.0341	*
X_3^2	22.97	1	22.97	14.41	0.0067	**
Residual error	11.16	7	1.59			
Missing fit	8.49	3	2.83	4.24	0.0983	
Pure error	2.67	4	0.67			
Sum	126.61	16				

Note: *Significant (p<0.05); **Extremely significant (p<0.01).

According to the variance analysis, the quadratic terms of excavation angle and forward speed have extremely significant influence on the stability coefficient of ditch depth. The quadratic terms of excavation clearance angle have significant influence on the stability coefficient of ditch depth, while the other terms are not significant. According to the coefficient analysis of the regression model, the main and secondary factors affecting the stability coefficient of trench depth are: the angle of entry, the angle of entry clearance, and the working speed. The response surface analysis (Figure 8) intuitively shows the relationship between test factors



a. Y=f (X_1,X_2,0) b. Y=f (X_1,0,X_3) c. Y=f (0,X_2,X_3)

Figure 8 Response surface of influence of each factor on evaluation index and indicators. When the entry angle remains unchanged, the stability coefficient of the trench depth first increases and then slowly decreases with the increase of the entry clearance angle. The stability coefficient of ditch depth increases with the increase of the angle of entry clearance when the angle of clearance is kept constant. As shown in Figure 8b, entry angle has a more significant influence on the stability coefficient of trench depth than forward speed. The stability coefficient of the ditch depth increases with the increase of the entry clearance angle when the forward speed is kept constant.

In order to obtain the optimal parameter combination, global multi-objective optimization is carried out based on the regression equation. The optimization equation is as follows:

$$\begin{cases} \max Y = (X_1, X_2, X_3) \\ \text{s.t.} \begin{cases} 20 \le X_1 \le 30 \\ 4 \le X_2 \le 8 \\ 0.5 \le X_3 \le 0.9 \end{cases} \end{cases} \tag{10}$$

The optimal working parameter combination was obtained as follows: chisel-shaped fertilization shovel entry angle of 30°, entry clearance angle of 8°, forward speed of 0.7 m/s.

5 Field test of rotary tillage and stubble disposal combined trenching device

The optimum working parameters of the rotary tillage stubble disposal device and chisel-type fertilizer shovel are as follows: the number of stubble-breaking knives is five, blade installation angle is 16°, chisel-type fertilizer shovel entry angle is 30°, entry clearance angle is 8°, and forward speed is 0.7 m/s. Under this parameter combination, field tests based on the whole machine were carried out in the seed planting park of Jade Tea Garden in Liangzihu District, Ezhou City, Hubei Province, as shown in Figure 9.

The stable area of the stroke was selected as the test area, and a total of three stroke operations were carried out, with each stroke length being 30 m. The 2 m unstable area at the beginning and end of the test was removed, and five measuring points were randomly selected along the normal direction of the machine to measure the depth and width of the trench. The test measurement results are listed in Table 4.

a. Field experiment process b. Rotary tillage and stubble throwing effect c. The effect of ditching

Figure 9 Field experiment effect

Table 4 Measured values of ditching depth and width

Travel	Test point	Depth/ mm	Width/ mm	Average depth/mm	Average width/mm	Stability coefficient of depth/%
First travel	1	179	239	196	222	93.73
	2	208	228			
	3	188	221			
	4	194	219			
	5	212	204			
Second travel	6	174	211	194	220	92.89
	7	216	248			
	8	194	233			
	9	187	209			
	10	198	202			
Third travel	11	207	219	195	230	91.74
	12	218	246			
	13	184	231			
	14	191	223			
	15	173	230			

As can be seen from Table 4, the trenching width of the rotary tillage trenching device ranges from 202 to 248 mm, the average width is 224 mm, the trenching depth ranges from 173 mm to 218 mm, the average trenching depth is 194.9 mm, and the average trenching depth stability reaches 92.78%, which can realize deep fertilization in the tea garden with a stable trenching depth.

6 Conclusions

1) In view of the difficulty of deep fertilization and trenching in tea gardens caused by the excessive stubble of deciduous tea branches on the surface of tea gardens, a rotary tillage and stubble disposal device was adopted to clean up the leaves, tea branches, and weeds between rows, followed by a ditching device with combined rotary tillage and chisel shovel for lateral deep fertilization in tea garden by means of a gouge-shaped fertilization shovel. Field experiments showed that the ditch width of the rotary tillage ditching device ranged from 202 to 248 mm, the average width was 224 mm, the ditch depth ranged from 173 to 218 mm, the average ditch depth was 194.9 mm, and the average ditch depth stability reached 92.78%, which could realize stable and deep lateral fertilization in tea gardens.

2) The effects of the number of stubble blades and the installation angle of blades on the stubble removal rate and the uniformity of stubble removal were studied by single factor test under different tool speeds. The test results showed that the stubble removal rate was the highest when the number of stubble blades was five, and it could reach 90.67% under fast speed. When the blade installation angle was 16°, the stubble removal rate was the highest, reaching 90.72% at slow speed and 91.64% at fast speed.

(3) The effects of the entry angle, clearance angle, and working speed on the stability of trench depth were studied by quadratic regression orthogonal rotation test. The test results showed that the primary and secondary factors affecting the stability coefficient of the trench depth of the chisel-shaped fertilization shovel were the entry angle, clearance angle, and forward speed. The optimization results showed that when the entry angle was 25°, entry clearance angle was 6°, and the forward speed of the machine was 0.7 m/s, the operation effect of the chisel-shaped fertilization shovel was the best.

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