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Article

Design and Experiment of the Combined Machine for Trans-Planting Outcrop of Codonopsis with Micro Ridge Covered with Film

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Abstract: In response to the problem of no supporting equipment for the cultivation of Codonopsis in the hilly and mountainous areas of northwest China, a combined machine for transplanting outcrop of Codonopsis with micro ridge covered with film is designed. The key components of the prototype are analyzed and designed, and the structures and working parameters of the seedbed preparation device, seedling casting device, rotary tillage soil-covering device, film covering device, seedling head burial and film edge soil-covering device are determined. The transmission system scheme is established, and the working mechanism of the core components is analyzed. Field experiments show that when the target seedling spacing is 4.4cm and the machines moves forward at the speed of 0.1, 0.15, and 0.2m/s, the variation coefficient of planting spacing and the qualification rate of planting depth all meet the standard requirements. The qualified rate of planting posture and film side outcrop are greatly affected by the operating speed of the machine, and decrease with the increase of operating speed. When the operating speed reaches 0.1m/s, the average variation coefficient of planting spacing is 0.08%, the average qualified rate of planting depth, planting posture and film side outcrop is 95.83%, 94.17% and 93.33% respectively, which shows that the operating performance is better than that of the operating speed of 0.15m/s and 0.2m/s. This study provides new reference for the theoretical research and design of mechanized and automated transplanting machinery for Codonopsis seedlings.

Keywords: mechanization; design; film side outcrop cultivation; Codonopsis

1. Introduction

Gansu Province is located at the intersection of the Loess Plateau, the Qinghai-Tibet Plateau and the Inner Mongolia Plateau. Its complex and diverse landforms, ecological and climatic conditions, and multi-ethnic settlement history have bred rich resources of Chinese medicinal materials. Among them, the output and market share of Codonopsis both account for more than 90% of the country[1], so Codonopsis has become an important source of farmers' income in the region. In order to reduce moisture retention and increase soil temperature, Codonopsis planting in this area adopts the film-covered outcrop transplanting technology[2,3]. At present, it is basically finished with manual operation without supporting equipment.

According to the falling posture of seedlings, transplanting mode can be divided into vertical planting, horizontal planting and oblique planting. In order to meet the planting mode and agronomic requirements of different plants, researchers have made many innovations and researches on transplanting machines. The self-propelled pepper transplanter designed by Md Zafar Iqbal et al. [4] has reduced the breakage rate of plastic film caused by working parts and improved the upright degree of seedling transplanting by analyzing and designing the working speed of the gear driven direct insert mechanism. Luhua Han et al. [5] proposed a self-propelled fully automatic rice

transplanter, which combined mechanical, electrical and pneumatic technologies to realize the automatic feeding and transplanting process of vegetable seedlings, greatly improving the planting efficiency. Xin Jin et al. [6] designed a vegetable single row transplanting device using mechatronics technology based on tomatoes, which can meet the high-speed transplanting requirements of vegetable seedlings. The above models are mainly used for vertical transplanting of vegetables and other crops. Other scholars carried out horizontal mechanized transplanting of some crops. Wei Yan et al. [7] designed a horizontal sweet potato transplanting machine to achieve horizontal transplanting of naked sweet potato seedlings, which saved labor and improved planting quality. In view of the oblique transplanting mode of naked seedlings, Xu Gaowei et al. [8] developed the oblique transplanting device on salvia miltiorrhiza film, Wu Guangwei et al. [9] developed the automatic transplanting machine of naked seedlings with sweet potato based on pre-treatment seedlings, and Wang Xujian et al. [10] developed the liquorice oblique transplanting ditch cutter. Mulching is essential in the process of pot seedling transplanting in dryland, the compound operation machine designed by Mingjun et al. [11] integrates hole, in-hole fertilization, transplanting, water injection and soil covering in the hole and mulching, which meets the requirements of mulching and drought resistance, but the film needs to be broken and seedlings be released in the later stage of planting. Dejiang Liu et al. [12] designed a dryland cantaloupe transplanting machine, which realized the precise formation of soil in the seeding hole and solved the problem of transplanting dryland cantaloupe. The whole machine adopted the method of mulching before breaking the film, which reduced the continuous insulation performance of the mulching film. In summary, the existing transplanting machine cannot meet the agronomic requirements of transplanting naked seedlings of *Codonopsis* while the labor intensity of manual transplanting and the planting cost is high.

In this paper, according to the agronomic requirements of *Codonopsis* transplanting, a combined machine for transplanting outcrop of *Codonopsis* with micro ridge covered with film is designed, and the field experiments are tested in order to provide a new reference for the theoretical research and innovative design of mechanization and automatic transplanting machinery of *Codonopsis*.

2. Structure and working principle of the machine

2.1. Agronomic requirements

Figure 1 is a schematic diagram of the cultivation mode of *Codonopsis* outcrop on micro ridge covered with plastic film. The height of ridge is 60~80mm, the row spacing is 700mm and 300mm, the film side outcrop width is 0~40mm, the oblique planting angle of the seedlings is 15°, and the plant spacing is 44mm. Two bundles of black mulch with a width of 620mm and a thickness of 0.01mm are selected to cover the two ridges with a width of 700mm.

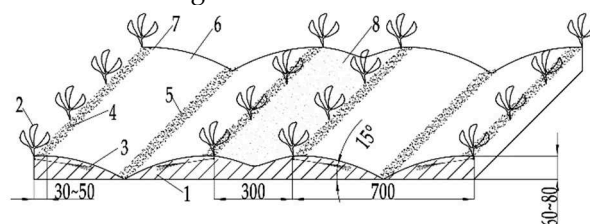







Figure 1. Schematic diagram of the cultivation mode of *Codonopsis* outcrop on micro ridge covered with plastic film. 1. Ridge body 2. Head of *Codonopsis* 3. Root of *Codonopsis* 4. Outcrop area on membrane side 5. Ridge soil-covering belt 6. Mulch 7. Film edge 8. Rain collecting surface.

2.2. Operation Procedure

The manual transplanting procedures of *Codonopsis* seedlings are shown in Table 1, which mainly include seedbed preparation, seedling placement, seedling soil-covering, film mulching, film edge and seedling head soil-covering.

Table 1. Manual transplanting operation procedure of *Codonopsis* seedlings.

NO	Process	Picture	Requirements
1	Seedbed preparation		The seedbed is tilted 10° to 20°
2	Setting seedlings		The head of the seedlings is aligned and the spacing is 40~60mm
3	Covering the seedlings with soil (burying the seedlings)		The thickness of covering soil is 40~80mm, and the soil should be scattered evenly
4	Mulching		The distance between film edge and head of the seedling is 0~40mm
5	Covering the membrane edge and seedlings with soil		The amount of soil covering for a length of 1000mm should not be less than 1.5kg

2.3. Structure and main technical parameters of the machine

As shown in Figure 2, the combined machine for transplanting outcrop of *Codonopsis* with micro ridge covered with film is mainly composed of frame, hanging device, seedbed preparation device, power transmission device, seedling casting device, rotary tillage soil-covering device, seedling head burial and film edge soil-covering device, etc. The seedbed preparation device, seeding device and rotary tillage soil-covering device are the main working parts, and the rationality of the design and configuration of these devices directly affects the operating performance of the whole machine. The main technical parameters of the machine are shown in Table 2.

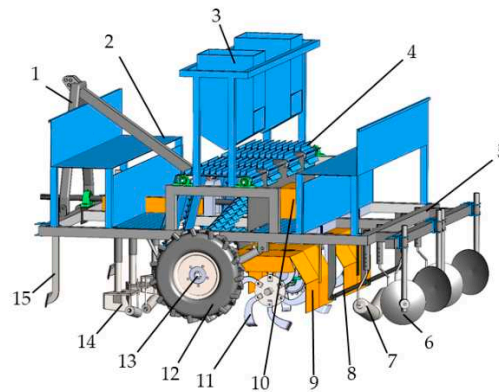


Figure 2. Overall structure diagram. 1. Hanging device. 2. Seat. 3. Seeding box. 4. Seedling casting device. 5. Frame. 6. seedling head burial and film edge soil-covering device. 7. Spreading film roll. 8. Film hanging frame. 9. Soil reflection device. 10. Gearbox. 11. rotary tillage soil-covering device. 12. Ground wheel. 13. Power transmission device. 14. Seedbed preparation device. 15. Ditching shovel.

Table 2. Main technical parameters of operating machine.

Parameters	Numerical Values
Machine dimensions (length × width × height)/(mm × mm × mm)	2297×2107×1655
Auxiliary power/kw	44.1
Overall quality/kg	512
Seedling placement method	Manual seedling placement
Seedling outcrop distance/mm	0~40
Plant spacing/mm	44
Productivity/(hm ² ·h ⁻¹)	0.45~0.65
Number of seeding rows	4
Angle of inclined planting/°	15
Covering thickness of seedlings/mm	40~80
Number of plastic films	2
The width of plastic film /mm	620
Suspension mode	Three-point suspension

2.4. Working principle

This machine can complete the ditching and ridging, seedbed preparation, seedling casting, seedling covering, film mulching, film edge and seedling head covering and other operations at one time. Before the operation, the seedlings are placed on the seeding device manually. The head of the seedlings should be aligned with the high position of the seedbed when placed. During operation, the whole machine is connected with the three-point suspension frame of the tractor through the suspension device. Under the pull of the tractor, the ditch shovel completes the work of ditching and ridging, then, the seedbed preparation device completes the ridge direction scraping, the extrusion of the seedling covering belt and the forming of seedbed along with the progress of the whole machine. The earth wheel transmits the power to the seedling casting device through the chain drive, and then the seedling casting device completes the transmission and casting of the seedlings. The tractor will pass the power through the gearbox to the rotary tillage soil-covering device which will cut the soil in high speed and the cut soil is thrown to both sides of the seedbed to cover the seedlings. The film installed on the film hanging frame can be uniformly coated with the aid of the film spreading roller. Finally, the covering disk would cover the film edge with soil and backfill the ridge.

The seedling casting device can ensure the plant spacing is not affected by the advance speed of the whole machine by making the ground wheel drive the chain so that the seedling spacing is stable.

3. Design of main working parts

3.1. Seedbed preparation device

Seedbed preparation device is one of the core working parts of the combined machine for transplanting outcrop of *Codonopsis* with micro ridge covered with film. The design and spatial location of the shaper directly affect the quality of seedbed preparation and subsequent seedling casting, thus affecting the overall outcrop effect of *Codonopsis* seedlings after mulching. Therefore, according to its agronomic requirements, this paper has conducted the relevant analysis and calculation of the shaper to achieve the function of the seedbed preparation. At the same time, the soil-covering belt of seedlings is formed, which ensures the amount of soil thrown by rotary tillage. A seedbed preparation device is specifically designed, which is connected with the frame. The seedbed preparation device is composed of two shapers, each has a crushing roller and the distance between the two shapers is 200mm.

3.1.1. Structure and operation principle

As shown in Figure 3, the seedbed preparation device is mainly composed of shaper, crushing roller, crushing roller regulating rod, connecting rod of shaper, adjusting rod of shaper, etc. The structure size and spatial position of shaper directly affect the molding of ridge bed and the quality of collected soil in ridge and furrow. The shaper is made of 65Mn steel plate with a thickness of 10mm. The working surface is designed into a right angle trapezoid structure. The angle between the hypotenuse and the long right angle is 75° , which can ensure that the included angle between the seedlings and the horizontal plane is 15° . In order to ensure that the soil will not exceed the top of the shaper when scraping, the width of the shaper is set to be 330mm, and the length of the short side is 200mm. The shaper is welded on the connecting rod of the shaper. In order to meet the requirements of different ground conditions, the operator can adjust the shaper up and down through the adjusting rod of the shaper and the adjusting bolt. The crushing roller is installed on the shaper through the adjusting rod of the crushing roller, and its axis is parallel to the bevel of the shaper. The height of the crushing roller can be adjusted through the crushing roller adjusting rod and adjusting nut. The upper and lower height adjustment of the shaper and the crushing roller and the adjustment of the ground wheel of the operation machine jointly determine the depth of the shaper into the soil and the position of the crushing roller. The adjustable range of the shaper and the crushing roller is 0~150mm and 0~250mm respectively.

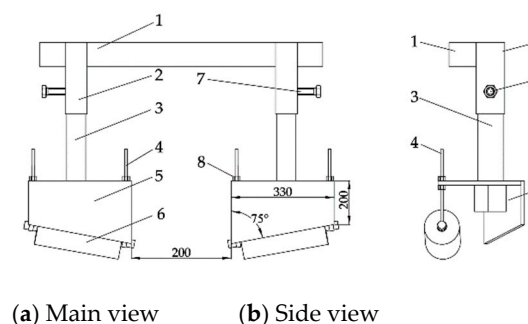


Figure 3. Structural Diagram of Seedbed Preparation Device. 1. Frame 2. Adjustment lever of shaper 3. Connection lever of shaper 4. Adjusting rod of crushing roll 5. Shaper 6. Crushing roll 7. Adjusting bolt 8. Adjusting nut.

Figure 4 shows the operation process of seedbed preparation device. In the process of seedbed preparation, while the shaper and crushing roller move forward, the crushing roller would crush the

soil and suppress soil moisture. The seedbed and seedlings soil-covering belt are formed after the soil is turned through the shaper. When the crushing roller contacts with the soil on the seedbed, it would roll and crush the soil to overcome the friction force and cohesion between seedbed and soil particles, compress the gravity water, attached water and the space between soil particles in the soil layer, and discharge the air in the soil layer[13] so as to ensure the soil particles are closely arranged and the seedbed is flat, thus avoiding the instability of plant spacing, the overall deviation of the seedlings and poor outcrop.

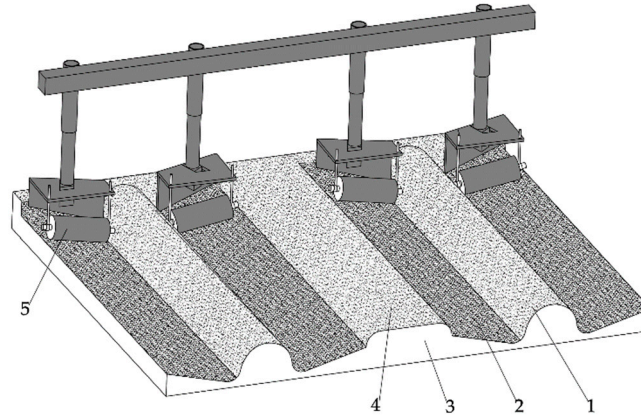


Figure 4. Schematic Diagram of Operation Process of Seedbed Preparation Device. 1. Seedling soil-covering belt 2. Seedbed 3. Ridge body 4. Non-working area 5. Seedbed preparation device.

3.1.2. Theoretical aggregate amount of soil

As shown in Figure 5, while moving forward, the shaper needs to push soil in front, transport the soil to the lateral side and extrude the soil so as to form the soil-covering belt of seedlings. In order to make sure the amount of soil collected on the soil-covering belt of seedlings and the thickness of the covering soil on the seedlings in the subsequent rotating tillage process, the amount of soil collected by the shaper needs to be calculated theoretically. The area of soil collection is calculated through the effective cross-sectional area of the shaper multiplies a certain length, and then the advance distance of the whole machine equals to the amount of collected soil Y

$$Q_1 = \gamma Y S_1 \quad (1)$$

$$\text{Where: } S_1 = h_z L_1 + \frac{L_1^2 \tan 15^\circ}{2} + L_2 (L_1 \tan 15^\circ + h_z)$$

Where Y is the advancing distance of the whole machine which is 1m

γ is the bulk weight of soil (yellow soil) (1300kg/m) [32].

S_1 is the cross-section area (m²)

h_z is the depth of the short side of the shaper into the soil (0.07m)

L_1 is the cross-sectional length of the shaper (0.25m)

L_2 is the distance between the two shapers (0.2m)

It can be calculated from Formula (1) that $Q_1 = 69.2\text{kg}$

When the advance distance of the whole machine is Y , the amount of covering soil required by the seedlings

$$Q_2 = \gamma Y S_2 \quad (2)$$

$$\text{Where: } S_2 = \frac{2HL_1}{\cos 15^\circ}$$

Where, the thickness of covering soil required by seedlings H is 0.07m.

It can be calculated from Formula (2) that $Q_2 = 37.6\text{kg}$

Because $Q_1 > Q_2$, the soil collection operation of shaper meets the theoretical requirement.

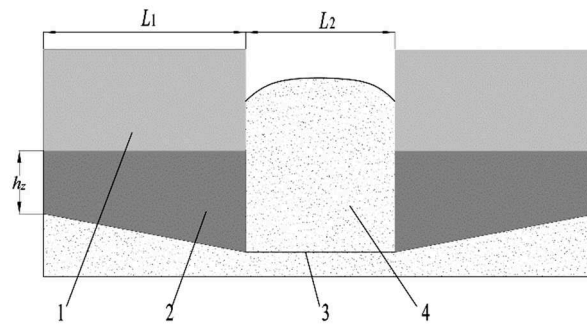


Figure 5. Schematic diagram of operation process of the effective cross-section of the shaper. 1. Bulldozing surface 2 Scraper plane 3. The action line of the rotary blade tip 4 The soil-covering belt of seedlings.

3.1.3. Mechanical analysis of shaper

In order to study the operation rule of the shaper for collecting soil in ridge and analyze the main influencing factors on the quality of collected soil in ridge, it is found that the quality of collected soil in ridge is not only related to the structural parameters and soil parameters of the shaper, but also to the installation angle of the shaper. Suppose the angle between the working surface of the shaper and the moving direction of the machine is α (that is, the installation angle α), then the larger the installation angle α , the larger the operation width, the greater the resistance of the scraper, which is prone to cause the soil be piled up[14–16]. If the installation angle α is too small, it can not meet the required width of seedbed, that is, the installation angle α should be reduced when the width of seedbed is met. In order to determine the mechanical conditions of soil scraping along ridges and furrows, it is assumed that there is no relative force between soil particles at the moment of sliding. There is no relative displacement between the soil particles and the working face of the shaper. Figure 6a shows the spatial mechanical analysis of the moment of slip of a single soil particle. Taking the soil particle center as the origin O , the direction parallel to the seedbed as x , the forward direction of the operating machine as y , and the direction perpendicular to the seedbed as z , the space rectangular coordinate system is established. Setting the direction of motion of a single particle at the moment of slip be A_z , it is seen that the operation surface slip of the shaper is reciprocated by the combined effects of normal force F_n , friction f and gravity G . Decomposing the above forces into the xOz coordinate system, as shown in Figure 6b, the resultant force F_x of the soil particle along the X -axis is

$$F_x = F_n \cos \alpha + G \sin 15^\circ - f \cos \beta \sin \alpha \quad (3)$$

Where, the angle β is the included angle of A_z projection on the surface ($^\circ$).

Taking the formula of friction f into formula(3)

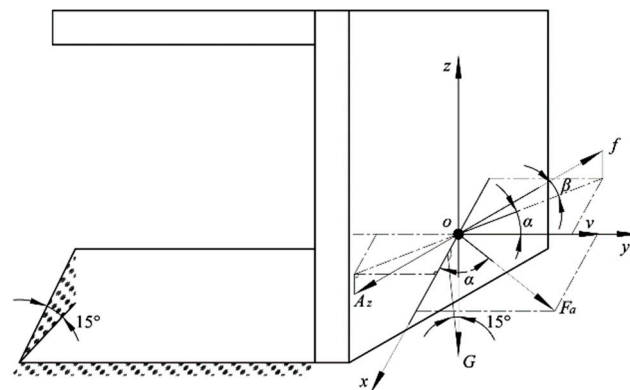
$$F_x = F_n \cos \alpha + G \sin 15^\circ - \mu F_n \cos \beta \sin \alpha \quad (4)$$

Where:

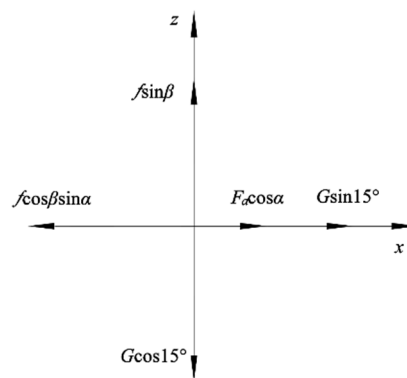
μ is the friction coefficient between soil particle and operating surface of shaper

G is gravity (N)

In formula (4), the friction coefficient μ between the soil particle and the operating surface of the shaper can be measured. The included angle β is related to the motion direction A_z at the moment of slip, The installation angle α can be determined by artificial adjustment, Soil particles will generally move in the positive direction of the x axis, and the mechanical condition is $F_x > 0$.



(a) Spatial force diagram



(b) Force on the xoz coordinate system

Figure 6. Spatial force analysis at the moment of soil particle slipping under the action of shaper.

According to the requirements of agronomy, the shaper should not cause soil to be piled-up greatly during its operation. When the curved form of the scraper is determined, the installation angle α is the key factor for the formation of the seedbed and the soil-covering belt of seedlings. Field experiments show that the width of seedbed can be guaranteed when the maximum installation angle α of ridge and furrow soil collection is 60° and the width of shaper is 330mm.

3.2. Seedling casting device

In order to ensure the alignment of the head of the seedlings when they are placed manually on the inclined plane of the seedbed, it is necessary to reasonably design the seedling casting device. Currently, the commonly used methods to control seedling spacing include pre-treatment of seedling belt method[9], hole disc seedling belt method[17] and artificial seedling feeding method[18]. Pre-treatment of seedling belt method requires a lot of preparation work and would consume much time, hole disc seedling belt method is suitable for transplanting seedlings with small plant spacing. Therefore, in order to improve the transplanting efficiency and meet the subsequent outcrop cultivation mode of membrane edge, this design adopts the way of artificial seedling feeding and mechanical auxiliary seedling casting. As shown in Figure 7, the seedling casting device consists of seedling protection plate, cylindrical pin, connecting block, fixed pin, seedling separation plate, conveyor belt, driving shaft of seedling casting device, driven shaft I and driven shaft II. They are fixed on the frame, relying on the rotation of the ground wheel to drive the driving shaft of the seeding device which rotates and drives the conveyor belt to move at the speed of V_c ; Driven shaft I and driven shaft II support the conveyor belt, and cooperate with it to move; Position m , n and e are seedling protection area, seedling casting area and seedling dropping area respectively. At point e , the seedling protection plate opens due to its dead weight, seedlings can be placed manually. When seedlings are transported to point m , the seedling protection plate closes under the action of gravity

to protect seedlings. When seedlings are transported to n point, the seedling protection plate opens to drop seedlings. The seedling casting device flexibly uses the self-weight of the seedling protection plate to realize real-time seedling protection and precise seedling casting.

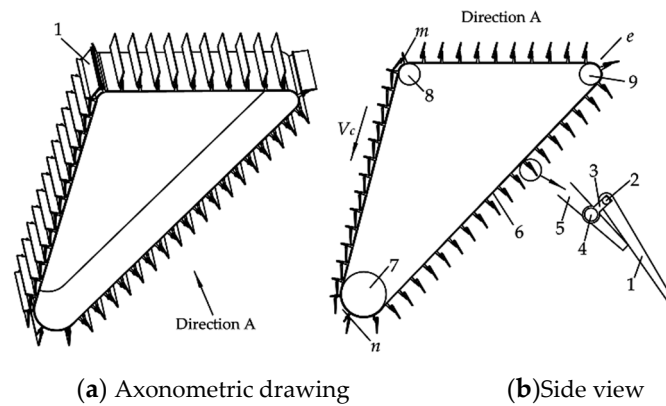


Figure 7. Structure of seedling casting device. 1. Seedling protection plate 2. Cylindrical pin 3. Connecting block 4. Fixed pin 5. Seedling separation plate 6. Conveyor belt 7. Driving shaft of seedling casting device 8. Driven shaft I 9. Driven shaft II.

3.2.1. Analysis of seedling movement

According to the cultivation mode of Codonopsis outcrop with micro ridge covered with film, it is necessary to carry out movement analysis of seedling landing process in order to ensure small head deviation of seedlings when they are thrown into the seedbed.

Figure 8a shows the side view of seedling casting process (the influence of seedling protection plate on seedling casting process is not taken into consideration), the driving shaft of seeding device rotates at angular velocity ω , V_m is the advance speed of the whole machine. Suppose that after seeding is thrown from point O of height H_1 , the head of seeding falls to point P and the root falls to point Q , and the horizontal displacement of seeding is L . Taking the horizontal direction as the x axis and the vertical plane as the y axis, a rectangular coordinate system is established.

Air resistance is considered in the seedling casting process, and it is known that the resistance of air is proportional to its motion speed[19], namely

$$f_a = \mu_1 V_t \quad (5)$$

Where f_a is the air resistance (N)

μ_1 is the coefficient of air resistance

V_t is the seedling speed, m/s

Without considering the slip of the conveyor belt, the instantaneous speed of seedlings leaving the conveyor belt is equal to the speed of the conveyor belt, namely,

$$V_t = V_c \quad (6)$$

V_c is speed of conveyor belt, m/s

The forces of seedlings during seeding operation are shown in Figure 8b. OP is the motion path of seedlings. At the moment when the seedlings leave point O , their motion are influenced together by gravity (mg) and air resistance (f_a).

Then the accelerated speed in all directions of the seedlings moving through the air is

$$\begin{cases} a_x = f_x / m \\ a_y = (mg - f_y) / m \end{cases} \quad (7)$$

Where a_x is the accelerated speed of the seedling in the horizontal direction (m/s^2)

a_y is the accelerated speed of the seedling in the vertical direction(m/s²)

f_x is the air resistance of the seedling in the horizontal direction (N)

f_y is the air resistance of the seedling in the vertical direction (N)

g is gravitational acceleration, m/s²

The instantaneous velocity V_c of the seedling is decomposed when the seedling leaves from the conveyor belt, and the velocity of the seedling in the x and y directions is

$$\begin{cases} V_x = V_m + V_c \cos \beta_1 \\ V_y = V_c \sin \beta_1 \end{cases} \quad (8)$$

By integrating Equation (7), the horizontal and vertical motion velocities of seedlings in the falling process can be written as V_{xt} , V_{yt} respectively

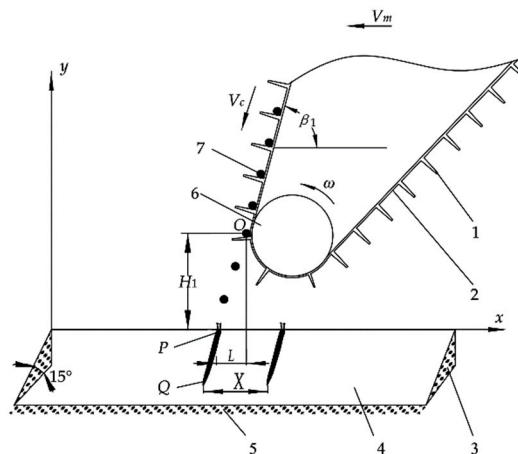
$$\begin{cases} V_{xt} = V_m + V_c \cos \beta_1 e^{-\frac{\mu_1 t}{m}} \\ V_{yt} = V_c \sin \beta_1 + g t - e^{-\frac{\mu_1 t}{m}} \end{cases} \quad (9)$$

V_{xt} is the motion velocity of seedlings in the horizontal direction (m/s)

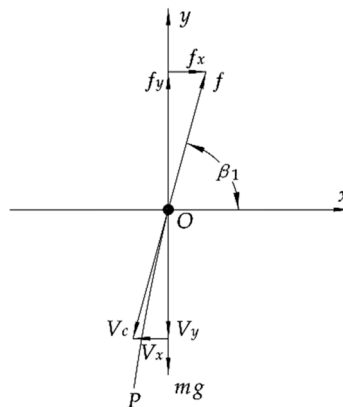
V_{yt} is the motion velocity of seedlings in the vertical direction (m/s)

β_1 is the angle between seeding direction and horizontal plane (°)

t is the movement time of seedlings (s)



(a) Side view of seedling casting process



(b) Seedling stress during seedling casting process

Figure 8. Analysis of seedling movement in the air. 1. Seedling protection plate 2. Conveyor belt 3. Cross section of seedbed 4. Seedbed 5. Seedling soil-covering belt 6. Driving shaft of seedling casting device 7. Seedling.

By integrating Equation (7) again, the displacement of seedlings in the horizontal direction x and in the vertical direction y is

$$\begin{cases} x=(V_m + V_c \cos \beta_1) \cdot t + \frac{m}{\mu_1} e^{-\frac{\mu_1 t}{m}} \\ y=V_c \sin \beta_1 \cdot t + \frac{g t^2}{2} - \frac{m}{\mu_1} e^{-\frac{\mu_1 t}{m}} \end{cases} \quad (10)$$

Through the motion analysis of seedling casting process, it can be seen that the larger the angle between seedling-casting direction and horizontal plane, the smaller the horizontal displacement. The velocity of the conveyor belt is positively correlated with the horizontal displacement. When the speed of conveyor V_c , the forward speed of machine V_m , the height of seedling-casting H_1 is determined (vertical displacement is determined), then the horizontal displacement is a fixed value.

3.2.2. Analysis of the collision process between seedlings and seedbed

According to the characteristics of the seedbed, the head of the seedling contacts with the seedbed first in the falling process. After that, the smaller the instantaneous velocity of the seedling, the smaller the deviation of the seedling. According to the law of conservation of momentum

$$MV_0 = MV'_0 + \sum_{i=1}^n m_i V_i \quad (11)$$

Where M is total mass of seedlings (g)

V_0 is the instantaneous velocity of seedlings while contacting with the seedbed (m/s)

V'_0 is the instantaneous velocity of seedlings after colliding with seedbed(m/s)

m_i is the mass of single soil particle (g)

V_i is the instantaneous velocity of a single soil particle after collision (m/s)

Equation (11) shows that the velocity of seedlings after collision is V'_0

$$V'_0 = V_0 - \frac{\sum_{i=1}^n m_i V_i}{M} \quad (12)$$

It can be seen from the above equation that after the collision between the seedlings and the inclined plane, in order to make the instantaneous velocity of the seedlings V'_0 small (the deviation of the seedlings should be small after the collision), the soil on the seedbed should not be too solid.

Through the analysis of the collision process between the seedlings and the seedbed, it can be seen that whether the seedlings can be cast successfully is related to the angle between the direction of seeding and the horizontal plane β_1 , and the soil firmness of the seedbed. During the test, in order to reduce the influence of air resistance on the effect of seeding, the angle between the seeding direction and the horizontal plane should be large. After comprehensive consideration, it is reasonable to set β_1 to be 60° , while the seeding height H_1 is low, so it can be set to be 80mm.

3.3. Rotary tillage soil-covering device

Rotary tillage knife can throw soil from lateral side[20,21], while in operation, the tractor will transfer power to the gearbox to change the speed of the power and drive rotary tillage soil-covering device work, the rotary tillage knife would break soil on the seedling soil-covering belt, ditch and throw soil on both sides of the seedbed to complete the seedling soil-covering operation. In order to

ensure that soil covered on both sides of the seedbed is uniform in the process of rotary tillage, the rotary tillage knife on the cutter head adopts the external installation method, and the rotary tillage knife at both ends of the cutter head bends outwards. The rotary tillage knife arrangement is shown in Figure 9.

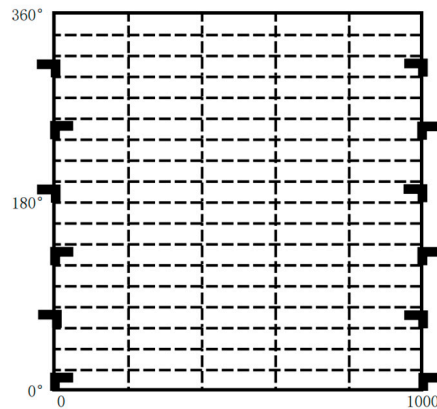


Figure 9. Schematic diagram of rotary tillage knife arrangement.

3.3.1. Analysis of soil-covering amount of rotary tillage knife

The rotating direction of the rotary tillage knife is the direction of soil throwing[22]. The process of the rotary tillage knife throwing soil is shown in Figure 10. The advance speed of the machine is V_m , the rotary tillage knife rotates at an angular speed ω_1 , and the soil is thrown up by the rotary tillage knife to position and cover the seedlings. In order to ensure that the thickness of covering-soil on seedlings is 40~80mm, it is necessary to analyze the soil-covering amount of rotary tillage knife on seedbed. Firstly, the soil cutting area of a single rotary tillage knife in a single rotation period is analyzed[23].

In order to establish the parameter equation of the soil disturbed by rotary tillage knife, the area of soil(S) cut by a single rotary tillage knife in a certain cycle is determined at first, then the thickness of soil(T) cut by a single rotary tillage knife in a certain cycle is obtained, and finally the area of soil(V) disturbed by rotary tillage knife is obtained. A rectangular coordinate system was established as shown in Figure 11. The motion curve of the blade end of the adjacent rotary tillage knife in the same direction in a certain cycle is established. The blade pivot(O_1) are taken as the center, the forward direction of the machine is the x -axis, and the vertical downward axis is the y -axis. The absolute motion of rotary tillage knife's end is the combination of rotation motion of blade pivot and forward motion of the machine, and the motion process of the end of rotary tillage knife meets the requirements of trochoid [24].

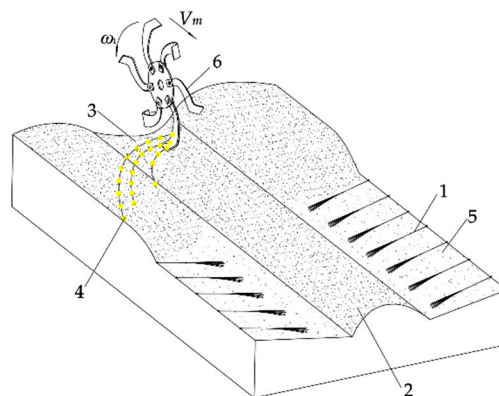


Figure 10. Schematic diagram of rotary tillage knife throwing soil. 1. Seedlings 2. Seedling soil-covering belt 3. Ridges 4. Soil particles 5. Seedbed 6. Rotary tillage knife.

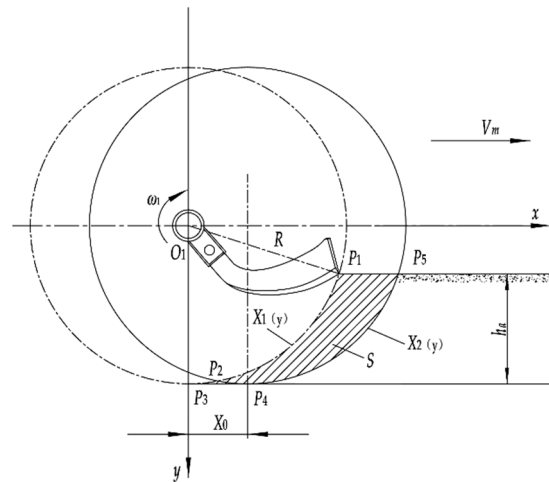


Figure 11. Area of soil cut by rotary tillage blade.

As shown in Figure 11, since the area enclosed by points P_2 , P_3 , and P_4 is torn apart by the cutter teeth during high-speed rotation, the soil cutting area S is enclosed by points P_1 , P_3 , P_4 and P_5 , the area of soil(S) cut by blade is enclosed by points P_1 , P_3 , P_4 and P_5 . The soil cutting area of a single rotary tillage knife in a single rotation period is expressed as

$$S = \int_0^{h_a} dy \int_{x_1(y)}^{x_2(y)} dx \quad (13)$$

Where:

$x_1(y)$ is the Equation of motion curve of the first rotary tillage cutter end

$x_2(y)$ is the Equation of motion curve of the second rotary tillage cutter end in the same period

The equation of motion curve of the first rotary tillage cutter end is

$$\begin{cases} x = R \cos(\omega_1 t) + V_m t \\ y = R \sin(\omega_1 t) \end{cases} \quad (14)$$

If the number of blades in the same direction is 3, then the lag soil-covering angle of the second rotary tillage knife in the same direction is $\frac{2\pi}{3}$, and the equation of motion curve of the second rotary tillage cutter end in the same direction is

$$\begin{cases} x = R \cos(\omega_1 t - \frac{2\pi}{3}) + V_m t + x_0 \\ y = R \sin(\omega_1 t - \frac{2\pi}{3}) \end{cases} \quad (15)$$

Where x_0 is the pitch of soil cutting, and its coordinates meet

$$x_0 = \frac{2\pi V_m}{Z\omega_1} \quad (16)$$

Where:

Z is the number of rotary tillage knife in the same direction, 3

By synthesizing Equations (13)~(16), it can be calculated that the soil cutting area S is

$$S = \int_0^{h_a} x_2(y) dy - \int_0^{h_a} x_1(y) dy \quad (17)$$

From the equation, the time t_1 , t_3 , t_4 and t_5 of rotary tillage knife pass through P_1 , P_3 , P_4 and P_5 can be calculated as

$$\begin{cases} \omega_1 t_1 = \sin^{-1}\left(1 - \frac{h_a}{R}\right) \\ t_3 = \frac{\pi}{2\omega_1} \\ t_4 = \frac{7\pi}{6\omega_1} \\ t_5 = t_1 + \frac{2\pi}{3\omega_1} \end{cases} \quad (18)$$

Where: t is time (s)

h_a is the tillage depth (mm)

R is the radius of rotary tillage knife (mm)

ω_1 is the angular velocity of rotary tillage blade (rad/s)

Combined with Equations (17) and (18), the soil cutting area S can be calculated as

$$S = \frac{A \cos 2\omega_1 t_1 + B \sin 2\omega_1 t_1 + C \cos \omega_1 t_1 + D \sin \omega_1 t_1 - \frac{1}{2} R^2 t_1 + E}{\omega_1} \quad (19)$$

Where:

$$\begin{cases} A = \frac{(\omega_1 + \sqrt{3})R^2}{8\omega_1} \\ B = \frac{(1 + \sqrt{3}\omega_1)R^2}{8\omega_1} \\ C = \frac{3\sqrt{3} + 3x_0 R + 3RV_m - 3\sqrt{3}\omega_1 RV_m t_1 - 2\sqrt{3}RV_m}{6\omega_1} \\ D = \frac{3 - 3\sqrt{3}RV_m t_1 - 3\sqrt{3}x_0 R + 2\pi RV_m + 3\omega RV_m t_1 + 3\sqrt{3}RV_m}{6\omega_1} \\ E = \frac{12\sqrt{3} + 14\pi RV_m - (6\pi + 3\sqrt{3} + 3\omega_1)R^2 - 12\sqrt{3}x_0 R - 2RV_m + \sqrt{3}\pi RV_m}{24\omega_1} - \frac{2RV_m + \sqrt{3}\pi RV_m}{4\omega_1^2} \end{cases} \quad (20)$$

The area of soil cut by a single rotary tillage knife in one rotation cycle can be approximately calculated as the product of the area of soil cutting and the thickness of soil cutting T , and the formula for calculating the thickness of soil cutting T is [25]

$$T = L_1 \sin(\pi - \theta) \quad (21)$$

Where L_1 is the cutting length of the rotary tillage knife's tangent edge, mm

θ is the Angle of tangent edge

According to Equations (19) and (21), the covering volume V of a seedbed soil-covering belt for one rotation of blade pivot is

$$\begin{aligned} V &= TSZ \\ &= \frac{3L_1 \sin \theta}{\omega_1} \left[A \cos 2\omega_1 t_1 + B \sin 2\omega_1 t_1 + C \cos \omega_1 t_1 + D \sin \omega_1 t_1 - \frac{1}{2} R^2 t_1 + E \right] \end{aligned} \quad (22)$$

According to Equations (18), (20) and (22), the volume of disturbed soil V is related to such parameters as ω_1 , R , L_1 , θ , h_a , Z and V_m . When the parameters of rotary tillage knife are determined, R , L_1 and θ are fixed values, so the soil-covering amount of seedbed is mainly affected by the depth of tillage h_a , rotary angular velocity ω_1 , numbers of rotary tillage knife Z , forward speed of machine V_m . When the forward speed of machine V_m is certain, the rotation angular speed and tillage depth are the main factors affecting the soil-covering thickness. Therefore, the adjustment of the depth of rotary tillage is taken into consideration in the design of the component.

3.3.2. Analysis of axial soil-transporting performance of rotary tillage knife

In order to ensure the axial covering range of soil while rotary tillage knife tilling soil, it is necessary to determine the mechanical conditions of soil axial movement. The force of rotary tillage is mainly determined by the structural parameters and soil parameters of rotary tillage. Suppose that there is no relative displacement of soil particles on the rotary tillage knife and there is no interaction between the soil particles. Figure 12 shows the spatial mechanical analysis of a single soil particle at the moment of separation. Taking the center line of the blade axis as the origin O_1 , the direction of the center line of the blade axis as x_1 , the direction of the machine as y_1 and the direction of the vertical horizontal plane as Z_1 , the origin of the coordinate system O_1 is translated along the plane $y_1O_1z_1$ to the center of the soil particle O_2 to obtain the spatial coordinate system. Suppose the instantaneous motion direction of the soil particle when it breaks away from the tangent plane of the rotary tillage blade be A_{z_1} , it can be concluded that the moment it breaks away from the tangent plane of the rotary tillage knife, it is affected by the comprehensive action of normal force F_n , friction force f_1 , gravity G_1 and centrifugal force F_c .

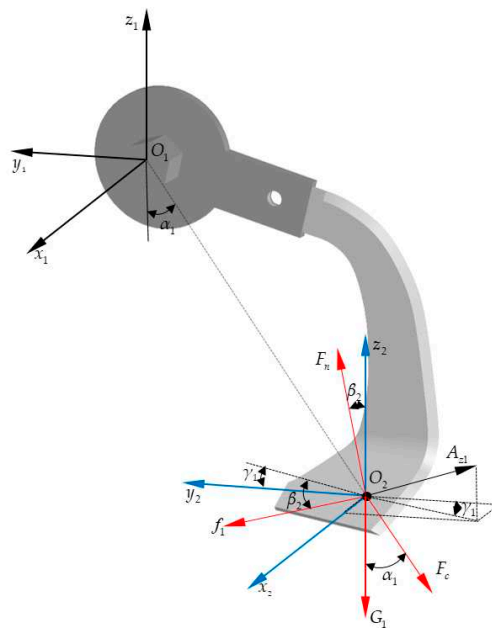


Figure 12. Spatial force of a single soil particle.

The stress of soil particles in $x_2o_2z_2$ coordinate system is decomposed into the coordinate system, as shown in Figure 13, the resultant force of soil particles along the direction of x_2 and z_2 are respectively

$$\begin{cases} F_{x_2} = \frac{F_c \cos \alpha_1 + G_1}{\cos \beta_2} \sin \beta_2 - f_1 \cos \beta_2 \sin \gamma_1 \\ F_{z_2} = F_n \cos \beta_2 - F_c \cos \alpha_1 - G_1 \end{cases} \quad (23)$$

Where α_1 is rotation angle of cutter shaft when soil particle is detached, ($^\circ$)

β_2 is angle between surface of $x_2o_2z_2$ and tangent edge of rotary tillage blade, ($^\circ$)

γ_1 is angle between projection of A_{z_1} on the surface of $x_2o_2z_2$ and y_2 axis, ($^\circ$)

F_{x_2} is the resultant force of soil particles along the x_2 axis, (N)

F_{z_2} is the resultant force of soil particles along the z_2 axis, (N)

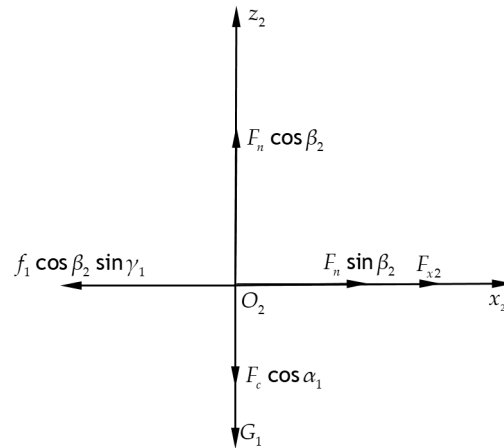


Figure 13. Stress of soil particles in $x_2o_2z_2$ coordinate system.

The expressions of centrifugal force F_c , gravity G_1 and friction f_1 are put into Equation (23) to obtain

$$F_{x2} = (m\omega_1^2 R \cos \alpha_1 + mg) \cot \theta - \mu_1 (m\omega_1^2 R \cos \alpha_1 + mg) \sin \gamma_1 \quad (24)$$

Where m is mass of soil particles (kg)

R is rotation radius of soil particle movement (mm)

μ_1 is friction factor between soil particle and surface of rotary tillage knife

g is acceleration of gravity (m/s^2)

θ is angle of tangent edge bend

In Equation (24), the relation between β_2 (the surface of $x_2o_2y_2$ and the tangent edge of the rotary tillage knife) and θ (the bending angle of the tangent edge) is $\beta_2 = \theta - \pi/2$, and the angle of the tool shaft α_1 ranges from 0° to 90° [25].

In order to determine the axial motion displacement conditions of soil particles, it is necessary to determine the motion process after the action of rotary tillage knife on soil particles. Setting the action time of rotary tillage knife on soil particles as t_1 , and the component velocity along the direction of x_2 at the moment when the soil particles leave the positive section of rotary tillage blade as v_x and the component velocity along the direction of z_2 as v_z , it can be obtained from the momentum theorem

$$\begin{cases} F_{x2}t_1 = mv_x \\ F_{z2}t_1 = mv_z \end{cases} \quad (25)$$

The motion process of soil particles on the surface of $x_2o_2z_2$ is shown in Figure 14. Suppose the vertical height between the moment when soil particles are thrown out and the head of the seedling is h , the component velocity on the surface of $x_2o_2z_2$ is V_1 , the rising height of soil particles after being thrown out is h_z , and the displacement of soil particles along the direction of x_2 is X_1 , and without considering the air resistance, then the time displacement relation is

$$\begin{cases} X_1 = v_x t_z \\ h_z = v_z t_{z1} - \frac{1}{2} g t_{z1}^2 \\ t_{z1} = \frac{v_z}{g} \\ t_{z2} = \sqrt{\frac{2(h+h_z)}{g}} \\ t_z = t_{z1} + t_{z2} \end{cases} \quad (26)$$

Where t_z is the time it takes for soil particles to fall to the head of the seedling after being thrown out (s)

t_{z1} is the time it takes for soil particles to rise to the highest point after being thrown out (s)

t_{z2} is the time it takes for soil particles to fall from the highest point to the head of the seedling (s)

g is acceleration of gravity (m/s^2)

According to agronomic requirements, the maximum displacement of soil particles X_1 along the direction of x_2 after being thrown out should meet

$$X_1 \geq l_1 / 2 \quad (27)$$

l_1 is spacing of wide line, which is set to be 700mm according to agronomic requirements

In combination with Equation (25) and (26), the displacement of soil particles X_1 along the direction of x_2 (covering width) can be calculated as

$$X_1 = \frac{F_{x2} t_1}{m} \left(\frac{F_{z2} t_1}{mg} + \sqrt{2 \left(\frac{h}{g} + \frac{F_{z2}^2 t_1^2}{2m^2 g^2} \right)} \right) \quad (28)$$

As can be seen from formula (28), factors affecting the landing position of soil particles are the vertical height between the moment when soil particles are thrown out and the head of the seedling (h), the resultant force F_{z2} of soil particles along the z_2 axis, the resultant force F_{x2} of soil particles along the x_2 axis, and the action time t_1 of rotary tillage knife on soil particles.

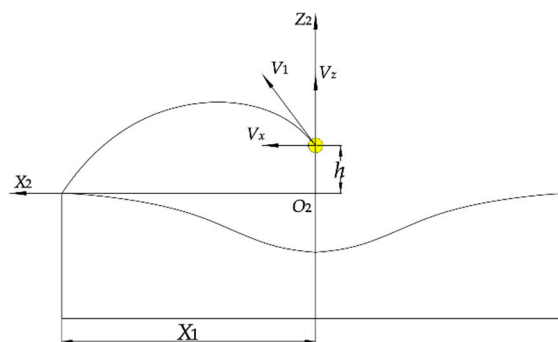


Figure 14. Movement process of soil particles on the surface of $x_2O_2Z_2$.

3.4. Film covering device

Figure 15 shows the structure of the film covering device, which is mainly composed of film hanging rod, connecting frame of film hanging rod, film spreading roll, adjusting rod of film spreading roll, connecting rod of film spreading roll, etc. The mulch extends from the hanging rod and is pressed to the V-shaped seedbed by the spreading roll, Both sides of the mulch are guided to

the seedbed by the spreading roller and are fitted with the soil, In order to prevent film damage in the mulching process, the two sides of the spreading roll are designed in circular arc, which can not only mulch the film, but also blanket the edge of the film. At the same time, the distance between head of the seedling and film edge ranges from 0-40mm, meeting the agronomic requirements of crop cultivation. The film height of the film spreading roll can be adjusted by changing the vertical position of the adjusting rod of the film spreading roll. Compared with the existing film covering device, the film spreading roll designed in this paper can realize V-shaped film coating and edge pressing under the premise of ensuring no damage to the film and improving the film coating quality of V-shaped seedbed.

According to agronomic requirements, the seedlings must outcrop on the edge of film in the process of film mulching, so the selection of mulching film needs to meet:

$$L \leq L_2 + 2L_1 - 2X \quad (29)$$

Where L_1 is the linear distance from the head of the seedling to the furrow (250mm)

L_2 is the width of furrow (200mm)

L is the width of film (mm)

X is distance between outcrop of seedling and film edge, which is set to be 40mm

Taking all the factors into consideration, the width of film is set to be 620mm.

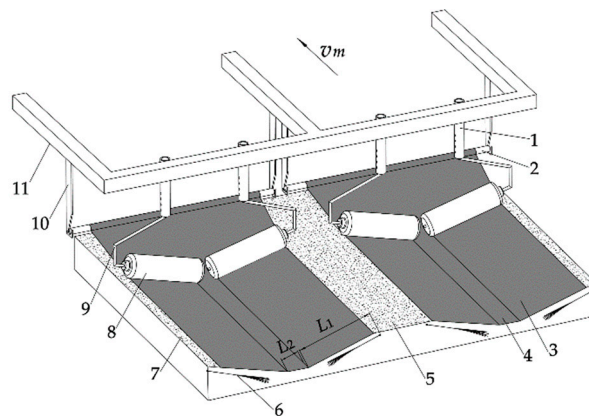


Figure 15. Structural diagram of film covering device. 1. Adjusting rod of film spreading roll 2. Film hanging rod 3. Plastic film 4. Mulching area on furrow 5. Rain collecting surface 6. Seedlings 7. Film side outcrop 8. Film spreading roll 9. Connecting rod of film spreading roll 10. Connecting frame of film hanging rod 11. Frame.

3.5. Seedling head burial and film edge soil-covering device

In order to prevent strong winds from uncovering the film, it is necessary to cover the film edge and furrow with soil[26]. At present, the common film covering device used are disc type, rotary tillage type, straddle type, etc. The disc type and plough-share type are usually given to the priority as they are easily to be adjusted, disassembled and transported in the process of operation. This design adopts the disc type as it can cover the film with soil effectively in low speed, at the same time, the chances of the soil to be piled-up is quite slim. Seedling head burial and film edge soil-covering device is composed of soil-covering disc, U-shaped card and so on. In order to adjust the thickness of soil covered on the film edge and furrow, the soil-covering disc is designed to adjust both the depth of the soil and the margin of the film.

As shown in Figure 16, during the operation of seedling head burial and film edge soil-covering device, it can cover soil on the edge of film; Under the action of gravity, the soil accumulated at the seedling head can backfill ridge furrow and press film[30] to form ridge furrow soil-covering belt. The amount of soil covered on the film edge and ridge furrow plays a very important role in covering soil on the film edge and constructing the mechanization of seedbed. The amount of soil lifted by the disc should be equal to the total amount of covered soil. In order to further improve the performance

of the seedling head burial and film edge soil-covering device, it is necessary to carry out theoretical analysis and calculation of the amount of covered soil.

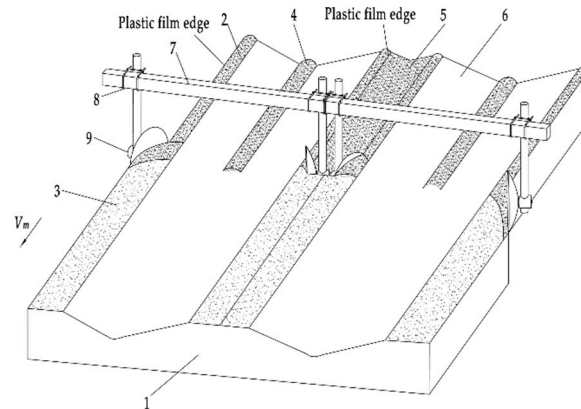


Figure 16. Schematic diagram of operation process of seedling head burial and film edge soil-covering device. 1. Ridge body 2. Film edge soil-covering belt 3 Field soil 4. Soil-covering belt on ridge and furrow 5 Rainwater collection surface 6 Plastic film 7 Frame 8 U-shaped card 9. Soil-covering disc.

Under the guidance of soil-covering disc, the edge of the film and ridges are covered with soil, and at last 4 pieces of film edge soil-covering belts and 2 pieces of ridge and furrow soil-covering belts are formed, each position of the mulched seedbed with a length of 1000mm is calculated.

Setting the amount of soil covered on the film edge as Q_3 , and the amount of soil covered on the ridge and furrow as Q_4 , then calculating the formula according to the amount of covered soil[31]

$$Q_3 = \gamma L_s B_1 H_1 \quad (30)$$

Where γ is bulk density of soil, which is set to be 1300kg/m³[32]

L_s is length of mulched seedbed, which is set to be 1000mm

B_1 is the width of film edge covered with soil (B), which is set to be 50mm

H_1 is thickness of film edge covered with soil (B), which is set to be 30mm

It can be calculated from Equation (30) $Q_3=1.95\text{kg}$

Similarly, the amount of soil covered on furrows is

$$Q_4 = \gamma L_s B_2 H_2 \quad (31)$$

Where B_2 is width of ridge and furrow covered with soil, which is 60mm

H_2 is thickness of ridge and furrow covered with soil, which is 35mm

It can be calculated from Equation (31) $Q_4=4.83\text{ kg}$

The total amount of covering soil is

$$Q_n = 4Q_3 + 2Q_4 \quad (32)$$

It can be calculated from Equation (32) that $Q_n=17.46\text{kg}$

The amount of soil lifted by a single soil-covering disk is[Error! Reference source not found.]

$$Q_{m1} = \gamma L_s S_2 \quad (33)$$

Where S_2 is the effective cross-sectional area of the soil-covering disc, which is set to be $4.3 \times 10^{-3} \text{m}^2$ in this paper

$$Q_m = 4Q_{m1} \quad (34)$$

Where Q_m is the total amount of soil lifted by the soil-covering disc

It can be calculated from Equation (34)

$$Q_m=22.36\text{kg}$$

It can be seen from Equations (32) and (34) that the total amount of soil lifted by the soil-covering disk Q_m is equivalent to the total amount of covered soil needed by the soil-covering belt Q_n , meeting the demand of soil-covering on the film edge.

3.6. The transmission system

The transmission system of combined machine for transplanting outcrop of *Codonopsis* with micro ridge covered with film is shown in Figure 17.

In the field operation, the machine adopts the three-point suspension mode at the rear of the four-wheel tractor and drives the trenching shovel to complete the trenching and ridging of the seedbed. At the same time, as the machine progress, seedbed preparation device would collect soil on ridge and furrow and form two V-shaped seedbeds; While the machine moves forward, the ground wheel is driven to rotate to input the power to the drive shaft of seedling casting device through the chain drive, then the driving shaft of seedling throwing device would rotate to drive seedling throwing device which will work together with drive shaft of seedling throwing device, driven shaft one and the second and third axles of driven shaft two to complete the artificial placement of seedlings; The power output shaft of tractor will input the power to rotary tillage knife of gearbox through the coupling, then rotary tillage knife of gearbox would cut the soil on the seedlings soil-covering belt and throw the soil onto two V-shaped seedbeds; Meanwhile, the mulching film rotates synchronously with the hanging frame, and the spreading film roller would mulch the film evenly and make sure the seedlings outcrop on the edge of film; Then 4 soil-covering disks would work together to cover the seedlings and press film.

In order to meet the agronomic requirements of seedling plant spacing, when the ground wheel rotates for one round, the driving shaft of the seedling casting device would rotate for n times, then

$$\frac{z_1 z_3}{z_2 z_4} = n \quad (35)$$

Where z_1 is the number of sprocket teeth of the ground wheel shaft, which is set to be 27; z_2 is the number of input sprocket teeth of intermediate shaft, which is set to be 13; z_3 is the number of output sprocket teeth of intermediate shaft, which is set to be 26; z_4 is the input sprocket teeth of driving shaft of the seedling casting device, which is set to be 12.

When the ground wheel rotates for 1 round, the number of seedings (n_1) delivered by each seedling casting device is

$$n_1 = n\pi d(1 + \varepsilon)/D \quad (36)$$

Where d is the diameter of the driving shaft of the seeding casting device, which is 100mm; D is the spacing between the seedling plates of the seeding casting device, which is taken to be 40mm; ε is the slip rate of the seeding casting device, which is 3%.

From Equation (36), it can be calculated that the seedling spacing X is

$$X = \pi d_1 / n_1 \quad (37)$$

d_1 is the diameter of the ground wheel (510mm).

By calculating formula (36) and (37), it can be obtained that when the ground wheel rotates for 1 round, the number of seedings delivered by each seedling casting device $n_1=36$, seedling spacing $X=44\text{mm}$.

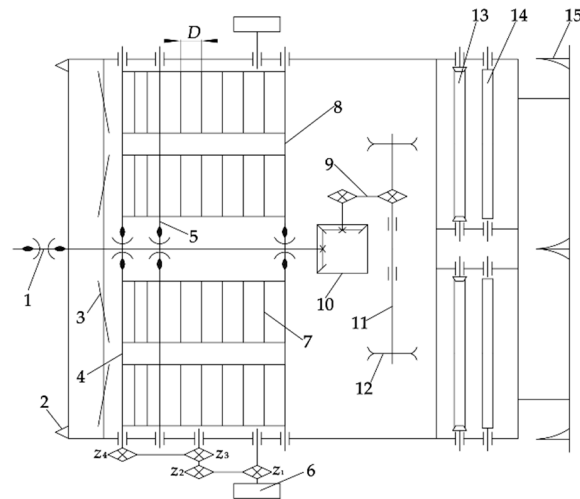


Figure 17. Schematic diagram of transmission system of combined machine. 1. Coupling 2. Trenching shovel 3. Seedbed preparation device 4. Driving shaft of seedling casting device 5. Driven shaft I 6. Ground wheel 7. Seedling casting device 8. Driven shaft II 9. Chain drive 10. Gearbox 11. Cutter shaft 12. Rotary tillage soil-cutting set 13. Hanging frame 14. Film spreading roller 15. Soil-covering disc.

4. Simulation of rotary tillage covering operation process

4.1. Setting of simulation parameter

Based on the above analysis, it can be seen that the rotary tillage knife adopts external installation method. In order to further determine the feasibility of lateral soil-covering method and verify the soil-covering quality of rotary tillage soil-covering device on seedlings, the discrete element method is used to carry out simulation test analysis on the lateral soil-covering performance of rotary tillage soil-covering device. The specific size of rotary tillage knife is shown in Figure 18. The covered soil particles were modeled as spherical particles, whose diameter was set to be 6mm, Hertz-mindlin(no-slip) was selected for the contact model of soil particle-soil particle, soil particle-rotary tiller and soil particle-seedbed, and the relevant simulation parameters were set as shown in Table 3[31].

Table 3. Parameters of simulation model.

Project	Parameters	Numerical value
Soil particles, V-shaped seedbeds	Poisson's ratio	0.4
	shear modulus /Pa	1.0×10^6
	Density /($\text{kg} \cdot \text{m}^{-3}$)	1364
Rotary tillage knife	Poisson's ratio	0.28
	shear modulus /Pa	3.5×10^{10}
	Density /($\text{kg} \cdot \text{m}^{-3}$)	7850
Soil particles - soil particles, seedbeds	Coefficient of recovery	0.21
	Coefficient of static friction	0.68
	Coefficient of dynamic friction	0.27
Soil Particles - Rotary tillage knife	Coefficient of recovery	0.54
	Coefficient of static friction	0.68
	Coefficient of dynamic friction	0.13

In combination with the characteristics of the seedbed, a V-shaped seedbed and soil reflection device are created in SolidWorks, setting the size of V-shaped seedbed (total length \times seedbed width \times ridge width) to be 3000mm \times 260mm \times 200mm and dip angle of the seedbed to be 15°. The V-shaped seedbed is imported into EDEM, and a virtual soil groove is established on the ridge, the basic size of the soil groove is set to be (length \times width \times height) 1000mm \times 200mm \times 300mm, and the virtual plane coexisting with the upper surface of the soil groove is set as a particle factory to generate soil particles at the rate of 3×10^4 /s with a total number of 3×10^5 , which takes 10s to generate particles. After particles are generated, the soil groove is removed to let particles fall into the ridge freely.

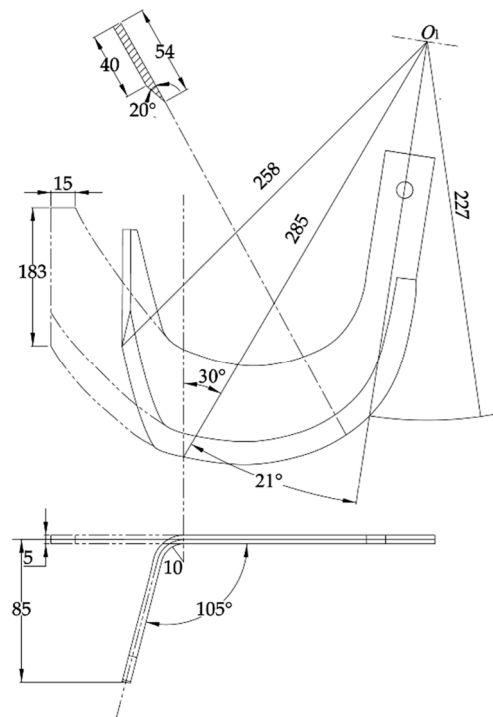
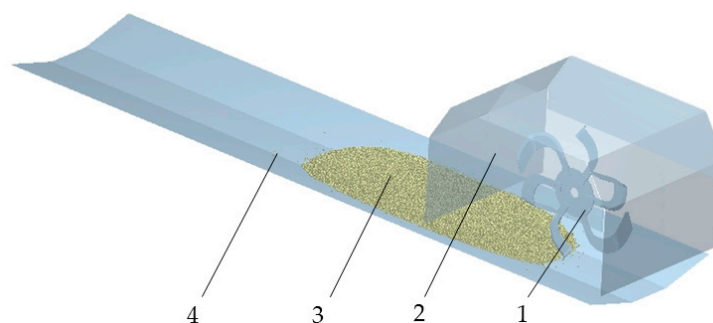


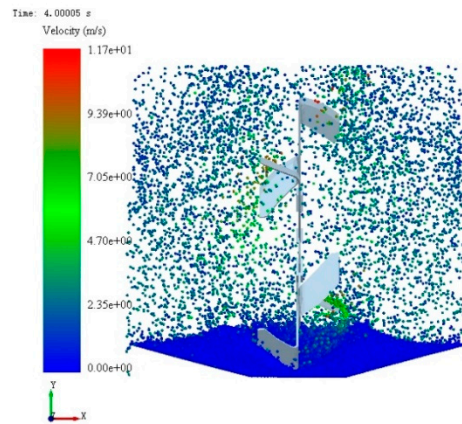
Figure 18. Structure diagram of rotary tillage knife.

4.2. Simulation process and result analysis

Before the simulation, SolidWorks is used to conduct 1:1 modeling of rotary tillage knife and soil reflection device, then the modeling is imported into EDEM after completion. At the beginning of the simulation, the rotary tillage knife begins to operate at one end of the soil-covering belt of the seedling, as shown in Figure 19a. The forward speed of the rotary tillage knife is set as 0.2m/s, the rotational speed is set to be 300r/min, and the total time is set to be 9s. The stability stage of simulation is shown in Figure 19b.



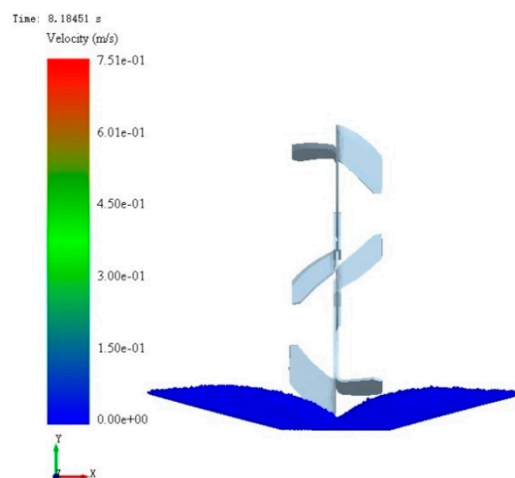
(a) Beginning stage of simulation. 1. Rotary tillage knife 2 Soil reflection device 3. Soil particles 4 V-shaped seedbed



(b) Stability stage of simulation

Figure 19. Simulation process.

Figure 20a shows the soil-covering effect of seedbed after simulation of rotary tillage. It can be seen from the simulation results that the rotary tillage covering device can backfill the soil into ridge furrow and form the ridge. At the same time, the covering width (Figure 20b) can reach 350mm, and the covering thickness (Figure 20c) can reach 71mm at the thickest point. The seedbed presents a shape of arc, and the soil particles on both sides of the seedbed is less. The main reason for this is that the soil particles collide with the seedbed in the process of falling, and the seedbed has a certain dip angle. The secondary soil-covering of the seedling can be completed in the subsequent burial of the seedling to cover the soil on the film edge so as to meet the requirements of the thickness of the seedling.



(a) Effect diagram of seedbed soil-covering after simulation

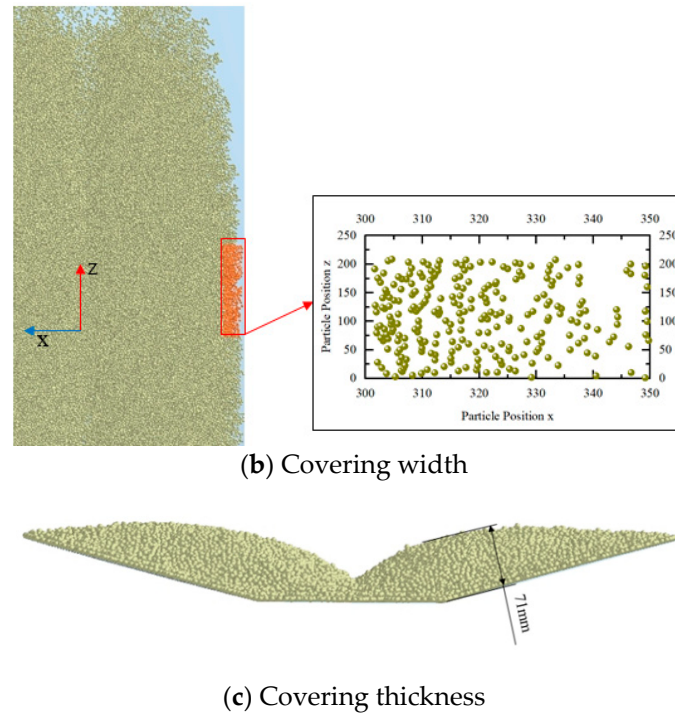


Figure 20. End of simulation.

5. Field experiment

5.1. Purpose and scheme design of the experiment

In order to check the working performance of the whole machine in the actual operation process, field working performance test of the prototype was carried out in the test field of Weiyuan County, Dingxi City in March 2023 (Figure 21).



Figure 21. Effect of Field Experiment.

Before the field test, the rototiller crushed soil in the field to ensure that the terrain of the test area was flat. The soil in the field was yellow loam soil, the moisture content was 12.2%, the surface temperature was 6.7°C, and the wind speed of the air near the surface was 1.29m/s. The tractor used to drive the machine was Dongfeng 554 tractor with climbing gear, the *Codonopsis* seedlings of 6 months were selected as the test seedlings, the average diameter of the seedling head is 3mm and the

average length is 110mm. the seedlings were tied with slip-knot before the test, the average number of each bundle is 175.

Performance tests were carried out with the forward speed of the tractor at 0.1 m/s, 0.15 m/s and 0.2 m/s respectively, and the output speed of the rotary tillage knife was 400r/min. At each forward speed, the depth of the rotary tillage knife was fixed at 220mm and the target seedling spacing was set at 4.4cm. Three groups of tests were carried out at each operating speed. Referring to JB/T 10291-2013 "Standard for dryland planting machinery", the standard deviation of seedling spacing, coefficient of variation of seedling spacing, qualified rate of film side outcrop, qualified rate of planting depth and planting posture were selected to comprehensively evaluate the accuracy of seedling spacing and planting quality of the prototype.

5.2. Accuracy of seedling spacing

The intersection point between the head of a Codonopsis seedling and the seedbed is the planting point of the seedling, and the projection distance of the planting point of two adjacent Codonopsis seedlings on the edge of the film is the planting spacing of the two Codonopsis seedlings. The planting distance X_i of each group of Codonopsis seedlings is measured, and the accuracy of the seedling spacing is evaluated by the coefficient of variation, and the test results of the accuracy of seedling spacing are shown in Table 4.

Table 4. Test results of seedling spacing accuracy.

Number	Forward speed (m/s)	Average seedling spacing /cm	Standard deviation/cm	Coefficient of variation /%
1	0.10	4.54	0.40	0.09
2	0.10	4.57	0.41	0.09
3	0.10	4.56	0.31	0.07
4	0.15	4.85	0.88	0.18
5	0.15	4.91	0.86	0.17
6	0.15	4.84	1.02	0.21
7	0.20	4.90	1.73	0.35
8	0.20	4.80	2.16	0.45
9	0.20	4.65	1.89	0.41

5.3. Qualified rate of planting depth, planting posture and film side outcrop

In order to measure the planting depth, planting posture and outcrop distance on the membrane side of Codonopsis seedlings, before data collection, the horizontal distance L_s between the seedling head and the membrane edge after the membrane edge is vertically downward and the covering soil is set as the measurement standard for the membrane side outcrop. The angle between the naked seedling and the horizontal plane is set as φ , and the distance between the deepest part of the naked seedling and the ridge surface is measured as H_s (Figure 22).

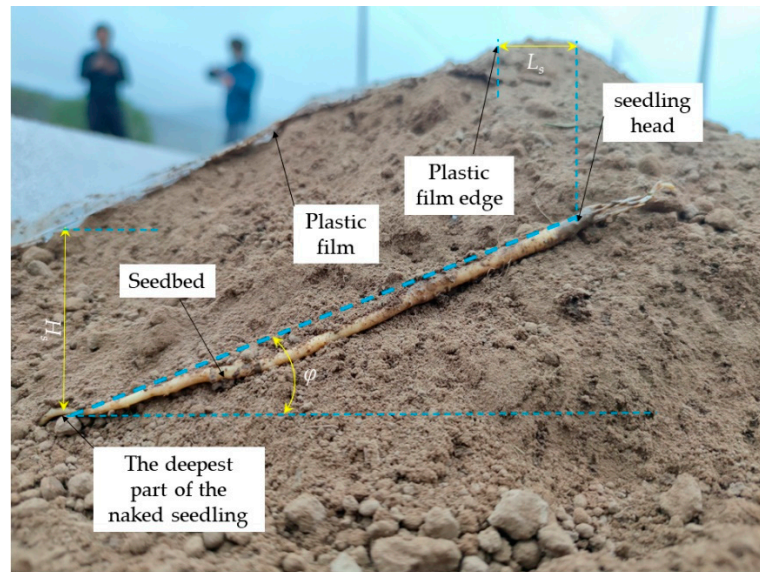


Figure 22. Schematic diagram of measurement of planting posture.

According to the agronomic requirements of *Codonopsis* seedling transplanting, when the planting depth meets the standard $4\text{cm} \leq H_s \leq 8\text{cm}$, the planting depth can be regarded as qualified. When the angle between the naked seedling and the horizontal plane meets the standard $10^\circ \leq \varphi \leq 20^\circ$, the planting posture can be regarded as qualified. When the horizontal distance between the seedling head and the membrane edge meets the standard $3\text{cm} \leq L_s \leq 5\text{cm}$, film side outcrop can be regarded as qualified. Suppose the total number of planted seedlings is N_t , the number of seedlings which meet the standard of planting depth is N_s , the number of seedlings meeting the standard of planting posture is N_z , the number of seedlings which meets the standard of film side outcrop is N_l , then the calculation method of qualified rate of planting depth P_s , the qualified rate of planting posture P_z and the qualified rate of the film side outcrop P_l are respectively as followings

$$P_s = \frac{N_s}{N_t} \times 100\% \quad (38)$$

$$P_z = \frac{N_z}{N_t} \times 100\% \quad (39)$$

$$P_l = \frac{N_l}{N_t} \times 100\% \quad (40)$$

The test results obtained from the above formula are shown in Table 5.

Table 5. Results of planting test.

Number	Forward velocity (m/s)	Number of plants	Number of qualified plants for planting depth	Number of qualified plants for planting posture	Number of qualified plants on membrane side outcrop	Qualified rate of planting depth /%	Qualified rate of planting posture /%	Qualified rate of film side outcrop /%
1	0.1	40	38	36	36	95.00	90.00	90.00
2	0.1	40	38	39	38	95.00	97.50	95.00

3	0.1	40	39	38	38	97.50	95.00	95.00
4	0.15	40	37	37	36	92.50	92.50	90.00
5	0.15	40	38	35	35	95.00	87.50	87.50
6	0.15	40	36	35	35	90.00	87.50	87.50
7	0.2	40	36	35	32	90.00	87.50	80.00
8	0.2	40	36	34	35	90.00	85.00	87.50
9	0.2	40	37	32	34	92.50	80.00	85.00

5.4. Discussion of test results

In the process of field test, the prototype can complete the operation process of seedbed preparation, seeding casting, rotary tillage soil-covering, film covering outcrop and film edge soil-covering at one time when the target seedling spacing is set at 4.4cm and the forward speed is 0.1, 0.15 and 0.2 m/s. When the machine moves forward at the speed of 0.1m/s, the average planting spacing was 4.56cm, the average variation coefficient of planting spacing was 0.08%, the average qualified rate of planting depth was 95.83%, the average qualified rate of planting posture was 94.17%, and the average qualified rate of film side outcrop was 93.33%. When the forward speed of the machine was 0.15m/s, the average planting spacing was 4.87cm, the average variation coefficient of planting spacing was 0.19%, the average qualified rate of planting depth was 92.5%, the average qualified rate of planting posture was 89.17%, and the average qualified rate of film side outcrop was 88.33%. When the forward speed of the machine was 0.2m/s, the average planting spacing was 4.78cm, the average variation coefficient of planting spacing was 0.40%, the average qualified rate of planting depth was 90.83%, the average qualified rate of planting posture was 84.17%, and the average qualified rate of film side outcrop was 84.17%. While the machine moves forward at the speed of 0.1, 0.15, 0.2m /s, referring to JB/T10291 -- 2013 "Standard for dryland planting machinery", variation coefficient of planting spacing is less than or equal to 20%, qualified rate of planting depth is greater than or equal to 75%, variation coefficient of planting spacing and qualified rate of planting depth both have reached the standard requirements. The variation coefficient of planting spacing becomes larger with the increase of forward speed, and the qualified rate of planting depth decreases with the increase of forward speed, indicating that the speed of prototype operation has a great influence on the seedling spacing and planting depth. There is no relevant standard requirements about qualified rate of planting posture and film side outcrop at present, so the qualified rate cannot be evaluated. It can be seen from the test results that qualified rate of planting posture and film side outcrop is greatly affected by the speed of machine and decreases with the increase of operation speed. It can also be concluded from the field test results that when the forward speed of the prototype is 0.1m/s, the operating performance is better than that of 0.15m/s and 0.2m/s.

6. Conclusion

(1) According to the agronomic requirements of *Codonopsis* membrane-side outcrop cultivation, a kind of combined machine for transplanting *Codonopsis* outcrop on micro ridge covered with film was designed, which can complete the seedbed preparation, seeding casting, rotary tillage soil-covering, film covering outcrop, seedling head burial and film edge soil-covering at one time. The machine is compact in structure and high in operation efficiency, which solves the problem that the *Codonopsis* can not be irrigated under the requirements of the dryland film mulching transplanting.

(2) This paper sets the relevant parameters of the core components of the whole machine and studies the working mechanism. In order to ensure the accuracy of transplanting and solve the

problem of high labor intensity of manual seeding, the machine adopts the way of manual seeding assisted with mechanical auxiliary seeding to realize the accurate placement of seedlings and automatic feeding; In order to make sure the seedbed to be formed and the amount of soil covered by rotating tillage operation, the installation angle of the shaper is set at 50°; In order to ensure the quality of seeding, the angle between the direction of seeding and the horizontal plane is set at 60°, and the height of seeding is set at 80mm; In order to ensure the range and amount of soil-covering seedlings, the rotary tillage knife is used to cut the soil, which makes it possible to adjust to the range and amount of soil-covering seedlings; While mulching device works, it can bury seedling head and cover soil on the edge of film with the assistance of seedling head burial and film edge soil-covering device.

(3) The field test results showed that the variation coefficient of plant spacing and the qualified rate of planting depth reached the standard requirements when the target plant spacing was 4.4cm and the working speed was 0.1, 0.15 and 0.2 m/s. When the working speed of the prototype increased, the plant spacing and planting depth were greatly affected. The qualified rate of the planting posture and the film outcrop was greatly affected by the working speed of the whole machine, and decreased with the increase of the working speed. When the machine moves forward at the speed of 0.1m /s, the average variation coefficient of planting spacing was 0.08%, the average qualified rate of planting depth was 95.83%, the average qualified rate of planting posture was 94.17%, and the average qualified rate of film side outcrop was 93.33%. The working performance was better than that of 0.15m /s and 0.2m /s.

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