



Article

Design and Experiment of the *Codonopsis pilosula* Outcrop Film-Laying and Transplanting Machine

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Abstract: A *Codonopsis pilosula* film-laying and outcrop transplantation machine is developed to solve problems, such as unstable quality of transplanted seedlings, high intensity of manual work, and low efficiency of work in the seedling transplantation of *Codonopsis pilosula*. This paper outlines the structure and working principle of the machine and analyzes the key components of the prototype, designs the seed bed preparer, analyzes its working process and the force required for furrowing into the soil. Additionally, based on EDEM discrete element simulation technology, a soil-component simulation model was established. In addition, the Hertz–Mindlin model was selected as the contact model between the discrete element simulation soil particles and the seed bed preparer to simulate the operation process of the seed bed preparer. The structure and relevant parameters of the seedling planting device and soil covering device are determined, the transmission system scheme is established, and the working mechanism of the core components is analyzed. Field experiment results indicate that at forward speeds of 0.20, 0.25, and 0.3 m/s, the average qualified rate of planting depth is 91.08%, and the average qualified rate of plant spacing is 89.8%. The field performance test indicators met national and industry standards, which require both qualified rates to exceed 80%, and the test results met the design requirements, demonstrating the integrated operation of trenching, seedling planting, film-laying, and topsoil covering.

Keywords: outcrop cultivation; seed bed preparation; *Codonopsis pilosula* transplanting machine; design; field experiments; discrete element method



Academic Editor: Murali Krishna Gumma

Received: 10 March 2025

Revised: 29 March 2025

Accepted: 15 April 2025

Published: 5 May 2025

Citation: Bai, J.; Sun, W.; Zhao, M.; Zhang, L.; Wang, J.; Simionescu, P.A. Design and Experiment of the *Codonopsis pilosula* Outcrop Film-Laying and Transplanting Machine. *AgriEngineering* **2025**, *7*, 131. <https://doi.org/10.3390/agriengineering7050131>

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1. Introduction

The Gansu Province is located at the intersection of the Loess Plateau, the Qinghai-Tibet Plateau, and the Inner Mongolia Plateau. With a large span of latitude and longitude, there are significant differences in altitude. The climate features include high altitude, cold and damp weather, drought, large temperature differences between day and night, strong solar radiation, etc., providing favorable conditions for planting *Codonopsis pilosula* due to its special climate and site conditions [1]. The total planting area of *Codonopsis pilosula* in China exceeds 53,333 hectares, with Gansu Province alone accounting for 50,666 hectares. The output and market share of *Codonopsis pilosula* in Gansu Province both exceed 90% [2]. Compared to regular trench cultivation, the yield increase per mu from above-ground

cultivation of *Codonopsis pilosula* reaches over 20% [3]. In order to improve the quality and yield of *Codonopsis pilosula*, outcrop cultivation technology has been adopted in this region. However, due to the lack of matching transplanting machinery, the transplantation of *Codonopsis pilosula* primarily relies on manual labor, involving four processes: trenching, sowing, mulching, and soil covering. Common issues such as unstable quality of transplanted seedlings, high labor intensity, and low operational efficiency significantly hinder the development of this technology.

According to the agronomic requirements of Chinese medicinal materials planting, relevant research institutes, universities, and enterprises have developed different kinds of Chinese herbal medicine transplanting machines, which can be generally summarized into three mechanized transplanting technologies: flat-working, inclined-moving, and vertical transplanting. Currently, the main transplanting methods used are flat-bed or inclined-bed transplanting. For example, Wang Junzeng and others from Gansu Agricultural University [4] have designed a *Codonopsis pilosula* seedling transplanting machine that meets the agronomic requirements for ridge mulching, row covering, and soil covering of *Codonopsis pilosula* seedlings in the arid regions of northwest China. This machine performs functions such as trenching, sowing, ridging, shaping, mulching, and row soil covering, effectively solving the problem of lack of suitable machinery for mulching and transplanting *Codonopsis pilosula*. However, the implement demonstrated relatively low average productivity ($0.14 \text{ hm}^2 \cdot \text{h}^{-1}$), with suboptimal film mulching and soil covering uniformity, coupled with high energy consumption. Yang Yong et al. [5] have designed an integrated machine for soil covering and mulching of *Astragalus* and *Codonopsis pilosula*. The designed soil throwing device can use a rotating soil throwing blade to throw soil into the wide trench in the middle. This effectively covers the seedlings of *Astragalus* or *Codonopsis pilosula*. The designed film covering mechanism can cover the edges of the plastic film with soil without damaging the seedlings, thereby improving the efficiency of transplanting operations, but the complex structural design complicates maintenance procedures, while the soil covering process may physically damage seedling crowns, ultimately compromising survival rates. Lai Qinghui et al. from Kunming University of Science and Technology [6] have designed a chain clip-type transplanting machine for *Panax notoginseng*. This machine uses a combination of manual seedling feeding and mechanical transplanting to reduce labor input, lower labor costs, and ensure uniformity in plant spacing, row spacing, and planting depth. However, the seedling gripper relies on spring-controlled clamping force, where inconsistent pressure may damage fragile rhizomes. Mao Guiling, Zhang Luhai, and others [7] have designed a rotary tillage inclined six-row *Codonopsis pilosula* mulching and fertilizing planting machine. This machine adopts a semi-automatic, manual-assisted method, integrating fertilization, mulching, and transplanting processes, resulting in a high survival rate of the transplanted seedlings. However, the implement exhibits critical limitations: inconsistent film mulching uniformity, elevated energy consumption, and inadequate seedling crown protection. Chen Hongxia and others from Inner Mongolia University of Technology [8] have designed an *Astragalus* transplanting machine that achieves horizontal transplanting of *Astragalus* and ensures uniform planting density, but there is a risk of damage to the seedling clamp, and the precision requirements for the fit between the guide rail and the seedling clamp are high; wear and tear can easily lead to seedling clamping failure. Wang Xujian and others [9] from China Agricultural University proposed the use of a licorice tilting transplant opener for the first time. Instead of a complex mechanical structure, the licorice tilting transplant opener achieved the tilting transplantation of licorice root seedlings through the opener operation process and controlled the soil backflow for the tilting transplantation of licorice root seedling. At the same time, a stable tilting seed bed was offered to achieve the tilting transplantation of licorice root seedlings without damage. There is

currently limited research on transplanting machines for exposed cultivation of medicinal herbs, but the structure is complex, the soil adaptability is limited, and the uniformity of trenching depends on the rotational speed. Yu Qingxu and others from the Nanjing Institute of Agricultural Mechanization [10] have designed a root and rhizome medicinal herb transplanting machine that processes outcropping, filming, and a roll-type mulching system, which takes an adjustable offset support component, allowing for adjustable row spacing from 900–1500 mm to 300–500 mm, effectively doubling the planting density and significantly increasing the yield of medicinal herbs. However, the efficiency of replacing spare seedlings is low, and the adjustment of multiple components relies on manual operation, which increases the labor intensity of operators. Although the operating efficiency of the above models has greatly improved compared to manual labor, there are problems such as uneven mulching and soil cover, low survival rate, complex structure, and even inability to ensure uniform row spacing for seedling transplantation. This does not meet the agronomic requirements for exposed cultivation of *Codonopsis pilosula* and can even lead to uneven emergence of seedlings, further affecting the mechanization of subsequent harvesting processes.

Therefore, this paper aims to design a *Codonopsis pilosula* mulching and exposed transplanting machine based on the agronomic requirements for *Codonopsis pilosula* cultivation. The seed bed preparer is employed to regulate soil return during operation, thereby providing a stable seed bed for the ginseng seedlings. The interplay between the seedling dropping mechanism and the mulching device facilitates the open-head cultivation of the *Codonopsis pilosula* seedlings, which enables the maintenance of consistent spacing between rows and rows of seedlings. This approach also results in a higher seedling emergence rate and yield compared to the traditional flat-rooted or slanting-shifted type. Field experiments were conducted on the entire machine, which could complete multiple procedures such as mechanical trenching, manual plant spacing, mechanical mulching, and mechanical soil covering in one operation to adapt to the use of small plots in hilly and mountainous areas.

2. Structure and Working Principle of the Entire Machine

2.1. Agronomic Requirements

Figure 1 shows a schematic diagram of the *Codonopsis pilosula* exposed cultivation model. The trench depth is 50 mm, and the row spacing is 500 mm and 400 mm. The seedlings are tilted at an angle of 25° during planting with a plant spacing of 40 mm. The seedling heads on the film side are exposed by 10–20 mm, and the soil covering thickness is 50–60 mm. A black plastic film with a width of 500 mm and a thickness of 0.01 mm is used to cover the ridge with a width of 500 mm [11,12]. The middle of the ridge has a rainwater collection micro-trench, and the bottom of the micro-trench on the film surface has permeable holes to ensure efficient use of rainfall.

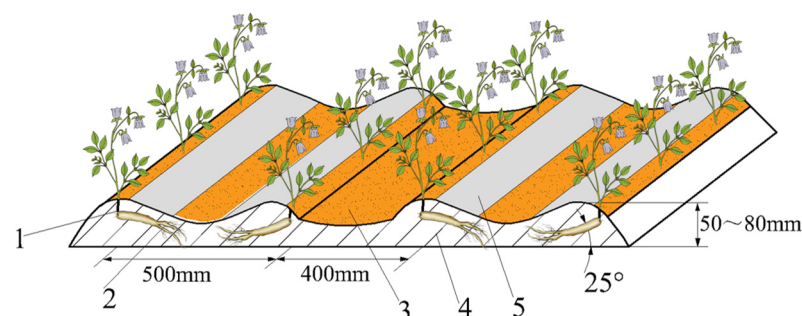


Figure 1. Diagram of *Codonopsis pilosula* cultivation in outcrop planting mode 1. 1. *Codonopsis* head, 2. *Codonopsis* root, 3. Covering the seedlings with soil, 4. Ridge body, and 5. Plastic film for ground cover.

2.2. Structure of the Whole Machine

As shown in Figure 2, the machine consists of a seed bed preparation device, a seedling planting device, a soil covering device, a film covering device, an offset mechanism, ground wheels, seedling boxes, seats, and other components.

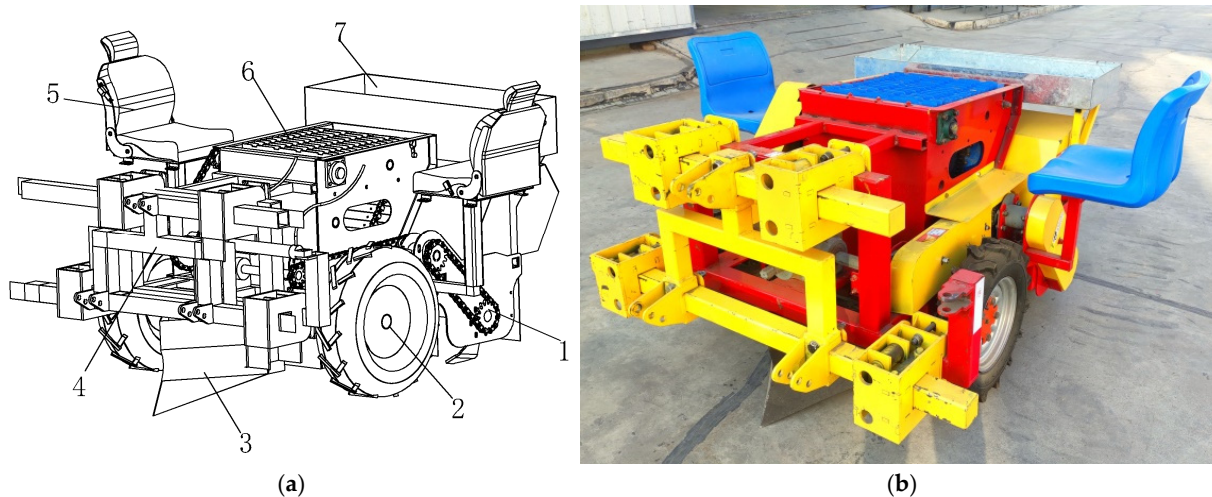


Figure 2. Structure of the machine: (a) Three-dimensional modeling diagram and (b) Prototype manufacturing drawings, with 1. Covering device, 2. Ground wheel, 3. Seed bed preparation equipment, 4. Bias pendulum mechanism, 5. Seat, 6. Seedling throwing equipment, and 7. Seedling box.

2.3. Working Principle

During operation, the *Codonopsis pilosula* outcrop film-laying and transplanting machine is connected to a tractor through a suspension mechanism. The machine is powered by a wheeled tractor. Under the traction of the tractor, the seed bed preparation device of the transplanting machine moves in a direction perpendicular to the ridge surface to complete trenching. The trench depth is 5 cm and the width is 50 cm. The ground wheels drive the rotation of the seedling planting device through a chain transmission. Operators manually place the *Codonopsis pilosula* seedlings on the seedling conveyor with the seed heads facing outward and the seed tails facing inward. The seedling conveyor transports the *Codonopsis pilosula* seedlings into the trench. Each trench plants one inclined seedling. Then the soil is covered on the *Codonopsis* seedlings with soil covering rotary blades on both sides of the machine. After soil covering, the root heads of the seedlings are 1–2 cm above the soil surface. The film covering device covers the film while simultaneously covering the soil. Finally, some soil is used to cover the sides of the film and the head portion of the seedlings through a chute, completing the entire operation process. After completing the transplanting in the first row, the hydraulic system of the tractor drives the motion of the offset mechanism, which moves the *Codonopsis pilosula* outcrop film-laying and transplanting machine to a suitable position for the next row of transplanting.

Since the machine adopts the method of manually placing seedlings, two people are required to continuously place seedlings on the seedling conveyor during the transplanting process. The frequency of supplying seedlings manually needs to be synchronized with the forward speed of the tractor. Therefore, it is required that the tractor can only be driven in a climbing gear during the forward process. This can effectively improve the efficiency of transplanting operations.

2.4. Main Technical Indicators

The *Codonopsis pilosula* outcrop film-laying and transplanting machine is designed for the double-row planting mode of *Codonopsis pilosula* in small plots in hilly and mountainous areas. The main technical parameters of the machine are shown in Table 1.

Table 1. Main technical parameters of *Codonopsis pilosula* open cultivation transplanter.

Parameter	Numerical Value
Dimension of the whole machine (length × width × height)/mm	2000 × 1650 × 1100
Machine mass/kg	5000
Structure form	Suspension type
Matching power range/kW	≥25.7 (with crawler gear)
Operating speed range/m.s ^{−1}	0.25~1.11
Working width/cm	90
Planting rows	2
Row spacing/cm	Wide range: 50; narrow range: 40
Hourly productivity/hm ² .h ^{−1}	0.19~0.38

3. Design of Main Working Parts

3.1. Bias Pendulum Mechanism

In the field of agricultural machinery, the application of the offset mechanism is mainly reflected in shock absorption and balance. On one hand, agricultural machinery often needs to operate on uneven terrain. In these cases, the machinery is prone to being affected by ground vibrations and bumps, which can affect the stability and efficiency of the machine. Therefore, some agricultural machinery equipment uses offset mechanisms to achieve shock absorption functions. On the other hand, in precision agriculture, agricultural machinery needs to be able to operate with precision to ensure crop growth and yield. In order to achieve this goal, some agricultural equipment used offset mechanisms for balance control [13]. In the design of the *Codonopsis pilosula* exposed film-laying and transplanting machine, the role of the offset mechanism is to reduce the issue of row spacing being wider than the tractor wheelbase. Since the tractor that drives the machine has a wider wheelbase than the machine itself, the actual transplanting row spacing is determined by the tractor's wheelbase. Without the offset mechanism, the row spacing would not meet the requirements, resulting in wasted land and insufficient plant density per acre. During the process of transplanting *Codonopsis pilosula* seedlings, the machine needs to always lean towards the side where transplanting has already occurred. This means that every time the direction of transplanting changes It means that the machine needs to be offset relative to the tractor.

Composition and Working Principle

A bias mechanism has been designed, as shown in Figure 3, which mainly consists of an offset connector, offset auxiliary ball bearings, fixed square tubes, hydraulic cylinders, hydraulic oil pipes, and suspension brackets. After the *Codonopsis pilosula* outcrop film-laying and transplanting machine completes one row of transplanting, the tractor's hydraulic system converts fluid pressure into mechanical energy through the oil pump to control the machine by driving the hydraulic cylinder. The hydraulic oil in the hydraulic system is sent into the pressure oil circuit by pressure, and the flow rate and pressure of the hydraulic oil are controlled by the regulating valve. The hydraulic oil is then transmitted to the hydraulic cylinder, which produces corresponding movement under the action of the hydraulic oil [14], thereby pushing the bias mechanism to work. The offset auxiliary

ball bearing inside the bias mechanism will be driven, thus driving the whole machine to move. The *Codonopsis pilosula* outcrop film-laying and transplanting machine can move left and right through the bias mechanism and then adjust the machine to ensure that the row spacing of the *Codonopsis pilosula* seedlings remains at a wide row of 400 mm, as shown in Figure 4. Then, the second row of transplanting begins, followed by the third row, using the same procedure. The travel range of the hydraulic cylinder, that is, the adjustable range of the bias mechanism, is from 0–260 mm.

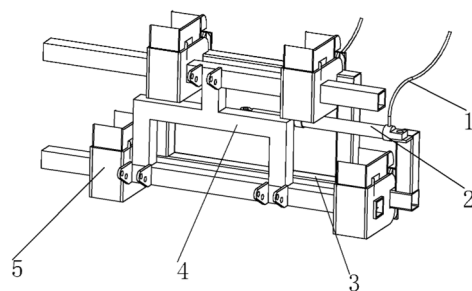


Figure 3. Bias pendulum mechanism with 1. Hydraulic fluid pipe, 2. Hydraulic cylinder, 3. Fixed square tube, 4. Suspension bracket, and 5. Bias connector.

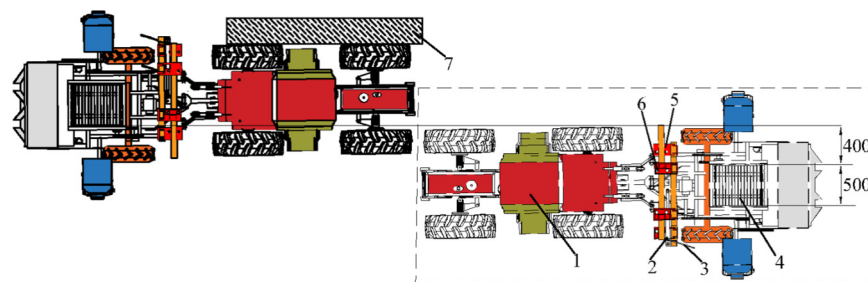


Figure 4. Schematic diagram of the bias pendulum mechanism, with 1. Tractor, 2. Hydraulic fluid pipe, 3. Hydraulic cylinder, 4. Transplanting machine, 5. Bias auxiliary ball, 6. Bias connector, and 7. Ground edge.

3.2. Seed Bed Preparation Equipment

The *Codonopsis pilosula* outcrop film-laying and transplanting machine mainly consists of seed bed preparation equipment and a seedling planting device. The seed bed preparation equipment provides a suitable bed for the growth of *Codonopsis pilosula* seedlings. The quality of the seed bed preparation affects the subsequent growth and yield of *Codonopsis pilosula*. The efficiency of the *Codonopsis pilosula* outcrop film-laying and transplanting machine is not only influenced by the seedling planting device but also constrained by the efficiency of the seed bed preparer. At the same time, the power of the transplanting machine is mainly consumed by the seed bed preparer. Selecting and designing a suitable seed bed preparer can effectively reduce production costs. Therefore, in this paper, based on the agronomic requirements of *Codonopsis pilosula*, a seed bed preparation device was designed, and relevant analysis and calculations were conducted for the seed bed preparer.

As a critical element for plant growth, soil provides nutrients and the necessary environment for the entire growth process. An appropriate seed bed for *Codonopsis pilosula* seedlings can provide sufficient nutrients and promote the growth of *Codonopsis pilosula* roots throughout the growth cycle [15]. In Gansu, the prolonged use of rotary plows has led to a shallow cultivation layer and an upward shift of the plow sole layer and thickening, which are unfavorable for *Codonopsis pilosula* to absorb nutrients and other growth factors from the soil during the growth cycle. According to the measurements of the mechanical and physical characteristics of the soil after crop harvest in Gansu, the

average cultivation depth in the region is 150–250 mm. To construct a suitable seed bed for the growth of *Codonopsis pilosula* seedlings, the cultivation depth was increased during seed bed preparation. However, the power consumption of the cultivation equipment is directly proportional to the cultivation depth. Taking into account the power consumption of the cultivation operation and the quality requirements of the seed bed, the cultivation depth during *Codonopsis pilosula* transplanting should be set at 50–80 mm with a trench width of 500 mm.

3.2.1. Structure and Working Principle

With the improvement of mechanical development level and the transformation of agricultural production methods, many types of ditching machines are in use currently. The disc opener effectively minimizes large-scale soil disturbance in the seeding zone, creating a narrow seed trench with a width of approximately 10 mm and a depth of up to 80 mm [16]. It demonstrates superior soil-cutting performance and low energy consumption; however, it fails to meet the depth and width requirements for exposed cultivation seed beds. In contrast, the moldboard opener exhibits strong penetration capability, making it suitable for hard or clay-heavy soils while maintaining stable trench depth and width. The plow-type furrow-opening machine has low requirements for pre-sowing preparation and forms a relatively flat bottom of the furrow, which is suitable for seed germination and growth. Therefore, it is widely used in small and medium-sized sowing machines [17]. However, the traditional ditching machine operation causes large soil moisture loss due to the backfill of dry soil in the surface layer and the overturning of wet soil in the bottom layer, which cannot meet the requirements of *Codonopsis pilosula*'s outcrop planting. Therefore, a seed bed preparer was designed for *Codonopsis pilosula*'s outcropping planting, as shown in Figure 5.

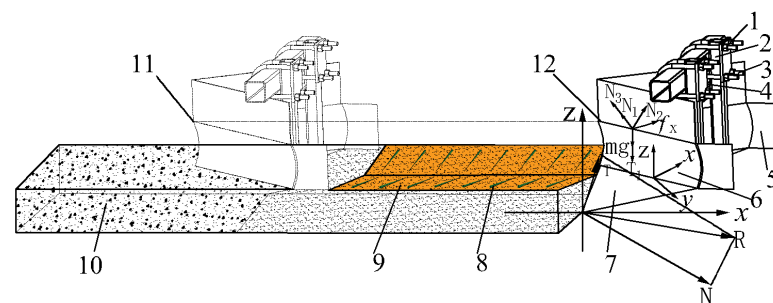


Figure 5. Seed bed preparation force analysis of the spar tip and at the soil diverter plate, with 1. Nut, 2. Shaper adjusting lever, 3. U-shaped screw, 4. Shaper connecting lever, 5. Soil retainer, 6. Soil diverter plate, 7. Share tip, 8. Chinese herbal medicine seedlings, 9. Seed bed, 10. Seed bed preparation equipment, 11. Plate, 12. Starting point for assignments.

It mainly consists of a furrow tip, a soil diversion plate, a soil-retaining plate, a shaper connecting rod, a shaper adjusting rod, a U-shaped screw, and a nut. The working surface of the shaper is in a triangular structure, and the hypotenuse is at a 65-degree angle with the furrow tip to ensure that the angle between the *Codonopsis pilosula* seedlings and the horizontal ground is 25 degrees. To meet the requirement of opening a 500 mm wide furrow for exposed planting, the distance between the soil-retaining plates on both sides of the shaper is designed as 500 mm. The shaper is fixed and connected to the frame by the connecting rod, adjusting rod, and U-shaped screw, which can be adjusted up and down to meet different requirements. When the seed bed preparer works, the shaper will cut into the soil to a certain depth according to the penetration angle, and the soil diversion plate will push the cut soil along the ridge line to split it into two parts. Then, the soil will move upward and be thrown to both sides after reaching a certain height along the soil diversion

plate. The soil-retaining plate will continuously compress the side of the furrow during the working process of the soil diversion plate to prevent backfilling, thereby forming a furrow with fixed depth and stable width [18], as shown in Figure 5.

3.2.2. Force Analysis of Seed Bed Preparation Equipment into the Soil

When the shaper starts the ditching operation, the furrow tip will perform the cutting and soil-breaking work, reducing the soil reaction force acting on the furrow tip [19]. By distributing the force horizontally, the soil penetration ability of the ditching machine can be effectively improved. The force analysis of the furrow tip is shown in Figure 5.

When the shaper is working under stable conditions, the furrow tip will be subjected to a forward pressure N , and the horizontal component force F is a constant. The value of F is determined by the soil resistance of the two-faced wedge under a specific tillage depth. In the figure, β represents the friction angle of the soil, which ranges from 25° to 35° [20]. Based on the actual situation of *Codonopsis* transplantation, the friction angle of the soil β is set to 30° . Therefore, the force R acting on the surface of the leveler can be indirectly represented by the combined force of the forward pressure N and the frictional force T acting on the tip of the blade. The force R acting on the soil deflector when the leveler is working can be expressed as:

$$R = F \sin \alpha^2 + F \sin \alpha \tan \beta \cos \alpha \quad (1)$$

$$R = F \left(\sin \alpha^2 + \frac{\sin(2\alpha)}{2} \tan \alpha \right) \quad (2)$$

where α represents the angle of soil entry. By taking the derivative of the equation and setting it equal to zero, we obtain the following formula:

$$\sin(2\alpha) + \frac{\sqrt{3}}{3} \cos(2\alpha) \quad (3)$$

From the above equation, we can determine the value of α that corresponds to the minimum point of the force R on the surface of the soil deflector. At this point, α represents the optimal angle of soil entry.

When the *Codonopsis pilosula* transplanting machine is performing field operations, the opening resistance experienced by the soil deflector is composed of the pressure exerted by the soil on the deflector and the friction between them [21]. The force acting on the soil deflector is shown in Figure 5.

The opening resistance F_y experienced by the soil deflector can be expressed as follows in the equation:

$$F_y = f_x + F_N \quad (4)$$

In the equation F_N is the pressure of the soil manifold by the soil, N and f_x is the friction of the soil manifold by the soil, N .

When the *Codonopsis pilosula* transplanting machine is operating in the field, the soil exerts a certain amount of support force on the soil deflector of the leveler, including the support force of the ground on the soil deflector, the support force of the soil on both sides of the ridges on the soil deflector, and the support force of the soil extrusion resistance on the soil deflector [22]. Since the self-weight of the soil deflector mainly acts on the side of the ridge, the support force of the ground on the soil deflector is not included in the calculation of frictional force. The frictional force can be expressed as follows in the equation:

$$f_x = \mu[(mg + T_1) \sin \beta + N_3] \quad (5)$$

where μ is the friction factor of soil and soil manifold; m is the mass of the shaper; T_1 is the support force of both sides of the monopoly body on the soil manifold; and N_3 is the support force of the soil extrusion counterforce on the soil manifold.

When the structural parameters of the *Codonopsis pilosula* transplanting machine are determined, there will be a certain angle formed by the difference in width between the front and rear of the soil deflector, which is known as the slope angle. The soil extrusion resistance will be affected by the slope angle, and the greater the slope angle, the more significant the opening resistance experienced by the soil deflector will increase. Conversely, if the slope angle is reduced, the opening resistance experienced by the soil deflector will decrease.

3.2.3. Simulation of the Interaction Mechanism Between Seed Bed Preparation Equipment and Soil

Determination of Soil and Machine Parameters

In order to explore the optimal working parameters and operational performance of the new seed bed preparer, a simulation analysis of the ditching process was conducted. The experimental soil used was sandy loam, which is loose and compressible. The physical properties of the soil include particle size distribution, soil density, shear modulus, Poisson's ratio, etc. [23]. The contact parameters include restitution coefficient, static friction coefficient, and rolling friction coefficient. After obtaining the basic parameters required for soil discrete element simulation through literature research. A simulation analysis of the ditching process of the seed bed preparations was conducted and is shown in Table 2. The primary parameters were selected based on existing literature [24–27].

Table 2. Simulation parameters of discrete element method for soil.

Parameter	Value
Soil particle density (kg.m^{-3})	2600
Soil yield strength (MPa)	0.23
Soil coefficient of restitution	0.6
Steel density (kg.m^{-3})	7850
Steel Poisson ratio	0.3
Steel shear modulus (MPa)	7.9×10^4
Coefficient of static friction between soil and implements	0.5
Coefficient of dynamic friction between soil and implements	0.05
Coefficient of restitution between soil and implements	0.6

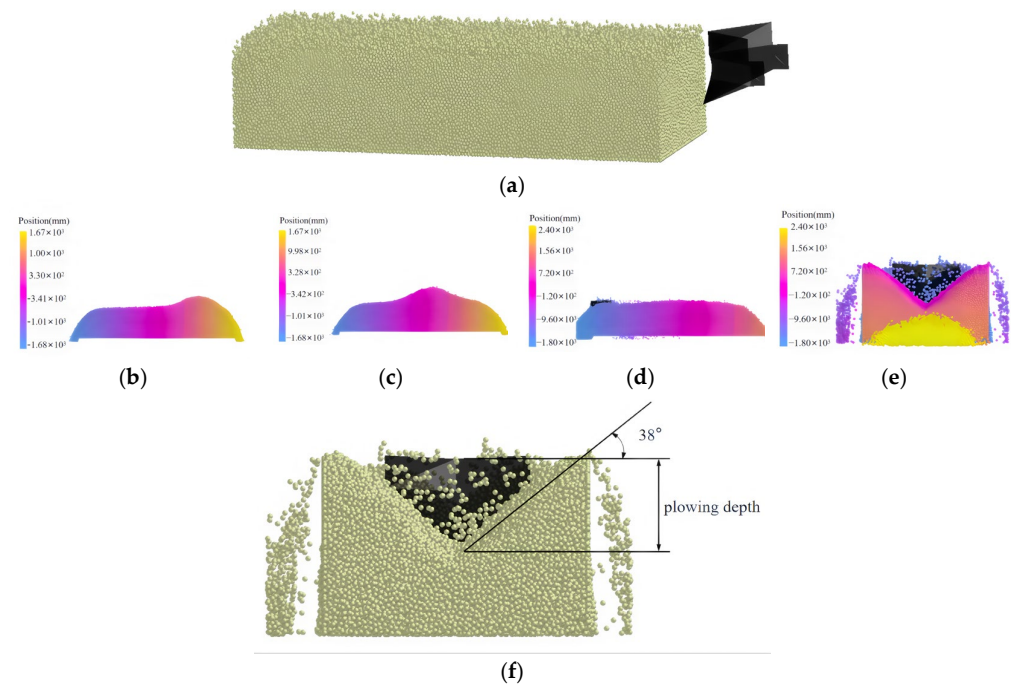
Discrete Element Simulation Modeling and Analysis

Currently, the particle size of soil modeling used in discrete element simulation research for cultivation is generally larger than the actual size of soil particles. Considering the simulation accuracy and computer performance, this study uses a variable-diameter spherical particle model to replace the actual soil particles, and the particle size range and ratio are shown in Table 3. The mass fraction set in the particle size range is based on the average value of the measured mass fraction, and the simulated particle size is ten times the arithmetic mean of the actual soil particle size [28].

As shown in Figure 6, The EDEM software was used to simulate the operation process of the seed bed preparer, which mainly includes the contact and collision between soil particles and the soil-contacting parts. The key is the contact model between soil particles. Common contact models in the EDEM 2020 software include the Hertz–Mindlin (no slip) model, Hertz–Mindlin with Bonding model, JKR model, Linear Cohesion model, Linear Spring model, Moving Plane model, etc. In this study, we do not consider heat transfer and wear issues and use the common Hertz–Mindlin (no slip) model as the contact model between the discrete element simulation soil particles and the seed bed preparer.

Table 3. Particle size distribution and mass fraction of EDEM soil particles.

Actual Particle Size/mm	Diameter of Simulated Particles/mm	Mass Fraction/%
0~0.1	1	13.81
0.1~0.5	3	28.89
0.5~1.0	7.5	26.57
1.0~2.0	15	14.04
>2.0	20	16.72

**Figure 6.** Simulation stages: (a) test tank establishment, analysis of seed bed preparation and soil particle bed at different time points (b–e), and details of the simulation process (f).

Once the generation of the simulated particles was complete and their distribution was stable within the simulated soil, the 3D model of the seed bed preparator was imported into the EDEM 2020 software. Subsequently, the model was positioned at one end of the simulated soil trench. During the simulation process, the depth of the seed bed preparator into the soil could be adjusted to ensure the accuracy and reliability of the simulation results. Additionally, the reasonableness of the design was verified by verifying the width of the open furrow, the angle of the open furrow incline, and the horizontal plane. The final step was to set the forward speed of the seed bed preparator to 0.25 m/s for the simulation.

Through simulation experiments, the trenching process of the seed bed preparator can be analyzed and compared with the actual field test results. The results of the field experiment demonstrated that the seed bed preparator had a trenching depth of 65 mm and a width of 500 mm. The planting angle of the *Codonopsis pilosula* seedlings was observed to be 32°. As shown in Figure 6, depth can be adjusted on a case-by-case basis, width is 492 mm, and planting angle is 38°. The simulation results are within 5% of the experimental data and meet the requirements of *Codonopsis pilosula* outcrop cultivation. Therefore, the trench width and planting angle in the simulation results verified the correctness and rationality of the design.

3.3. Seeding Device

The seeding device is the core component of the *Codonopsis pilosula* uncovered film transplanting machine, and good seedling delivery performance is the basis for ensuring

planting performance. In order to meet the agricultural and planting requirements in China, some scholars have proposed various forms of seedling picking mechanisms, such as top-out, top-out and gripping, insertion and gripping, and pneumatic methods [29]. Although these methods have good seedling-picking effects, the seedling-picking trajectory is complex and affects the stability of seedling-picking. Therefore, in order to improve transplanting efficiency, this design adopts the method of manual seed placement with mechanical assistance in seed delivery. Future implementations could employ machine vision (e.g., RGB-D cameras or hyperspectral imaging) to achieve morphological recognition and precise positioning of Chinese medicinal herb seedlings [30,31]. Deep learning algorithms (YOLO, Mask R-CNN, etc.) may be adapted to accommodate the diversity of rhizomatous herbs like *Codonopsis* and *Astragalus*, while pneumatic soft grippers or biomimetic robotic arms could significantly reduce seedling damage rates [32,33].

As shown in Figure 7, the seedling delivery device mainly consists of a seedling groove driving gear, a seedling groove driving shaft, a chain, a seedling groove, a chain plate driving pulley one, a chain plate driving pulley two, a chain plate driving pulley fixed shaft, a bearing seat, etc. It is fixedly installed above the frame, and as the implement advances, the ground wheel drives the seedling groove driving gear to rotate. The seedling groove driving gear drives the seedling groove driving shaft to rotate at a speed of V , and then the seedling groove driving shaft drives the chain plate driving pulley fixed shaft to rotate. The seedling groove driving shaft and the chain plate driving pulley fixed shaft jointly maintain the reciprocating rotation of the seedling delivery chain plate. Manually place the *Codonopsis pilosula* seedlings parallel to both sides of the planting trench on each seedling groove. As the seedling delivery chain plate rotates, the seedlings are evenly placed in the soil, realizing accurate seedling delivery. The two main parts that drive the delivery of *Codonopsis pilosula* seedlings are the chain and the metal chain plate, which provide traction power through their cyclic reciprocating motion and serve as the carrier during the transportation process, respectively. The principle is mainly to use a series of chains fixedly connected to the traction chain to provide traction force and use a metal chain plate as a carrier to guide *Codonopsis pilosula* seedlings to be transported horizontally or vertically.

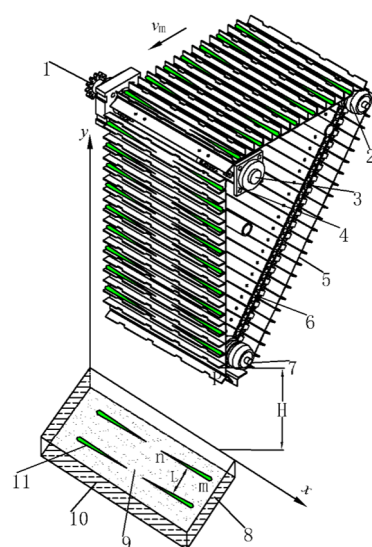


Figure 7. Seedling device (side view of seeding process) with 1. Seedling trough driving gear, 2. Chain plate transmission pulley, 3. Seedling trough driving shaft, 4. Bearing housing, 5. Seedling trough, 6. Chain, 7. Chain plate transmission pulley fixed shaft, 8. Seedling covering belt, 9. Seed bed, 10. Cross-section of seed bed, and 11. Seedling.

3.3.1. Analysis of Seedling Planting Movement

In order to determine the factors that affect the seedling delivery effect and to establish evaluation indicators for the seedling delivery experiment, the horizontal motion process was analyzed to determine the impact of the seedling delivery rate on the seedling delivery effect. The vertical motion process was also analyzed to determine the impact of the seedling drop height on the seedling delivery effect. Figure 7 shows a side view of the seedling delivery process, while V_m is the forward speed of the transplanting machine. Assuming that the head of the seedling falls into point m and the root falls into point n after being thrown out from point p at a height of H and the horizontal displacement of the seedling is denoted as L , a Cartesian coordinate system is established with the X -axis as the horizontal direction and the Y -axis perpendicular to the horizontal plane. It is known that the air resistance to the seedling is proportional to its movement speed [34]:

$$f = \mu v \quad (6)$$

where f is the air resistance, N; μ is the air resistance coefficient, and v is the seedling speed, mm/s.

The force acting on the seedlings during the seedling delivery operation is shown in Figure 8. At a certain moment during the seedling delivery motion, the seedlings are subjected to the forces of gravity and air resistance. Based on Newton's second law, we can establish a differential equation for the motion and explore the factors affecting seedling delivery.

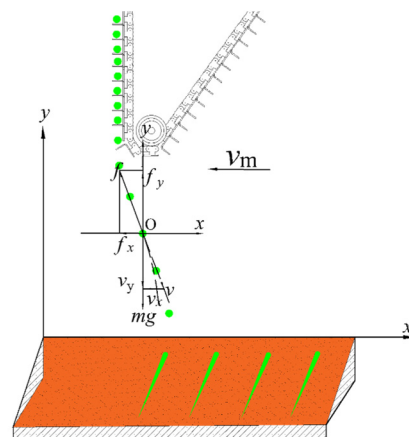


Figure 8. Force analysis diagram of seedling with f the air resistance, N; mg the weight of the burrow seedling, N; v is the speed of movement of the burrow seedling, mm/s.

3.3.2. Analysis of Horizontal Direction Planting Movement

By analyzing the horizontal motion process during the descent of the seedlings, we can explore the impact of the seedling delivery speed on the seedling delivery effect.

$$f_x = ma_x \quad (7)$$

where m is the mass of the seedling, g; a_x is the horizontal acceleration of the seedling, mm/s².

By integrating the above equation, we can obtain the horizontal velocity of the seedlings during motion as:

$$v_x = v_0 - e^{\frac{\mu \cdot t}{m}} \quad (8)$$

where v_x is the horizontal direction of the seedling movement speed, mm/s; v_0 is the seedling throwing speed, mm/s; and t is the movement time, s.

Integrating the above equation again, the horizontal displacement of the seedling can be obtained as:

$$L = v_0 t - \frac{m}{\mu} e^{\frac{\mu t}{m}} \quad (9)$$

where L is the horizontal displacement of the seedling, in mm.

3.3.3. Vertical Direction Seedling Throwing Motion Analysis

By analyzing the vertical motion process, we can explore the impact of the seedling drop height on the seedling delivery effect.

$$G - F_f = ma_y \quad (10)$$

where a_y is the vertical acceleration of the seedling, mm/s².

Integrate the above equation to get the vertical direction movement speed of the seedling as:

$$v_y = \frac{mg}{\mu} (1 - e^{-\frac{\mu t}{m}}) \quad (11)$$

where v_y is the speed of the vertical direction movement of the seedling, mm/s.

Integrating the above equation again, the vertical displacement of the seedling is obtained as:

$$y = \frac{m^2 g}{\mu^2} (e^{\frac{\mu t}{m}} - 1) \quad (12)$$

where y is the vertical displacement of the seedling, mm. Without considering the effect of μ on the effect of seedling casting, the vertical displacement is:

$$\lim_{\mu \rightarrow 0} y = \frac{m^2 g}{2\mu} \frac{t}{m} e^{\frac{t}{m}\mu} = \frac{1}{2} g t^2 \quad (13)$$

From the equation, it can be seen that when μ tends to 0, the value of y tends to approach $1/2 g t^2$. In this case, when the planting height is fixed and the vertical displacement is determined, the motion duration t of the seedlings can be determined. Moreover, the air resistance has almost no effect on the delivery of the seedlings. Since the displacement of the *Codonopsis pilosula* seedling depends on the initial speed of the *Codonopsis pilosula* seedling out of the seedling transporting chain plate and the height of the seedling, while the speed of the *Codonopsis pilosula* seedling in the seedling transporting chain plate is fixed, and the plant spacing of the ginseng is determined to be $n = 40$ mm, it means that the center distance between the two neighboring chain plates is 40 mm; therefore, the length of the chain plate of the seedling transporting chain in the vertical direction is taken as $L = 20$ mm. Therefore, the final design determines the length of the seedling groove in the vertical direction to be 800 mm.

The kinetic energy of the seedlings when thrown towards the ground can be expressed as:

$$T = \frac{m}{2} v_m^2 = \frac{m}{2} (v_x^2 + v_y^2) \quad (14)$$

where T represents the kinetic energy of the seedlings, measured in J.

Based on Equations (8) and (11), it can be inferred that for a single seedling, the mass m remains constant while the initial velocity v_0 , air resistance coefficient μ , and motion time t will affect the seedling's velocity. Similarly, from Equations (9) and (12), it can be inferred that for a single seedling, the mass m remains constant while the initial velocity v_0 , air resistance coefficient μ , and motion time t will affect the horizontal position of the seedling's landing point. Furthermore, considering Equation (14) as a whole, both the planting height and planting velocity will have an impact on the success rate of seedling transplantation.

3.4. Covering Device

After completing the procedures of trenching, seedling placement, and seedling delivery, the soil flipped from both sides of the trench should be compacted over the seedlings to improve their survival rate. As shown in Figure 9, the covering device of the *Codonopsis pilosula* mulch-laying and transplanting machine is mainly composed of a rotary tillage shaft, drive sprocket, soil covering rotary tillage blade, ridge-forming support, soil-guiding plate, soil-blocking plate, etc. When the machine moves forward, the power from the gearbox is transmitted to the covering device through the intermediate shaft, driving the sprocket to rotate, and then the sprocket drives the rotary tillage blade to start rotating and enter the soil. Due to the design of the rotary tillage blade and its rotating motion, it can form a curved cutting surface in the soil, separating the upper layer of soil from the lower layer [35]. The soil covering the rotary tillage blade flips the cut soil and covers it along the edge of the plastic film, completing the covering operation at the film edge. At the same time, some of the broken soil is flipped into the soil-guiding plate. During the forward movement of the *Codonopsis pilosula* mulch-laying and transplanting machine, the fine soil is axially conveyed through the soil-guiding plate, and the soil is scattered in the gap between the soil-guiding plate and the soil-blocking plate, evenly covering the film surface and forming two strips of soil, completing the seedling-covering operation.

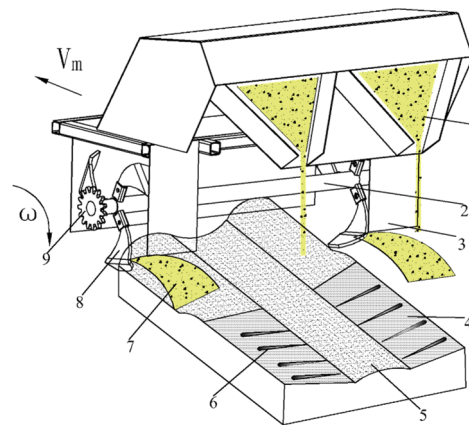


Figure 9. Soil covering device with 1. Soil guide plate, 2. Rotary tillage shaft, 3. Soil retaining plate, 4. Seed bed, 5. Seedling soil covering belt, 6. Seedlings, 7. Soil particles, 8. Soil covering rotary tillage knife, and 9. Driving sprocket.

Kinematic Analysis of Rotary Tiller Blade Motion

During rotary tillage operation, the rotary tillage blade moves forward with the machine tool while rotating, and the motion trajectory of each point is a trochoid. Under the same operating parameters, the motion trajectory equations obtained from forward and reverse rotations are identical [36]. This paper only presents the kinematic analysis of the rotary tillage blade's reverse rotation. A Cartesian coordinate system is established with the axis of rotation of the blade as the origin, and the direction of machine advancement is taken as the positive X-axis. During reverse rotation, the positive direction of the Y-axis is vertically upward, as shown in Figure 10.

As mentioned above, the coordinate system established at this point represents the reverse rotary ploughing motion with the equation of motion:

$$\begin{cases} x = R \cos(\omega t) + v_m t \\ y = R \sin(\omega t) \end{cases} \quad (15)$$

where R is the rotary radius of the rotary ploughing knife endpoint, mm; ω is the rotary angular speed of the rotary ploughing knife, rad/s; t is the movement time, s; and v_m is the forward speed of implements, m/s;

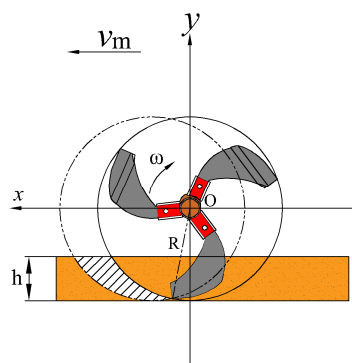


Figure 10. Motion of the reverse rotating tiller blade.

Through the derivation of the above equation, the rotary ploughing knife end point speed equation can be obtained as:

$$\begin{cases} v_x = dx/dt = v_m - R\omega \sin(\omega t) \\ v_y = dy/dt = R\omega \cos(\omega t) \end{cases} \quad (16)$$

where v_x is the rotary ploughing knife endpoint x -axis partial velocity, m/s; v_y is the rotary ploughing knife endpoint y -axis partial velocity, m/s.

Associating the above equation, the absolute velocity equation of the end point of the rotary ploughing knife is:

$$v = \sqrt{v_x^2 + v_y^2} = \sqrt{v_m^2 + R^2\omega^2 - 2v_mR\sin(\omega t)} \quad (17)$$

where v is the absolute speed of the rotary ploughing blade endpoint, m/s

From the above equation, it can be seen that during the motion of the rotary tillage component, the velocity of the blade endpoint continuously changes with time. When $V_x > 0$, there is mutual compression between the soil and the back of the blade, which can lead to soil accumulation in front and affect the operation of the machine. When $V_x < 0$, the cutting edge cuts the soil backward and throws it, allowing the rotary tillage blade to operate normally. Therefore, the component velocity of the blade endpoint in the x -axis direction must be less than 0.

Let the depth of ploughing of the rotary ploughing component be h ; then we have:

$$h = R - y = R - R\sin\omega t \quad (18)$$

and must be satisfied to be less than zero, then:

$$R > h + v/\omega \quad (19)$$

when the *Codonopsis pilosula* transplanting machine is operating normally, the forward speed of the unit, v , is within the range of 0.25 to 1.11 m/s. The rotary tillage depth, h , is between 50 and 80 mm. The rotational speed of the rotary tillage blade shaft is between 270 and 360 r/min, corresponding to a roller rotation angular velocity, ω , of 28.28 to 37.70 rad/s. By substituting the data into the equation for analysis and calculation, the rotating radius of the rotary tillage blade must be greater than 119.25 mm.

3.5. Transmission System Design

Compared to belt drives, chain drives exhibit a more compact structure, higher power transmission capacity, and superior overload tolerance, with reduced radial pressure on the drive shaft. When contrasted with gear drives, chain drives require lower installation precision and demonstrate significant cost advantages. Specifically optimized for agricultural applications, chain drive systems accommodate shaft center distances of 5–6 m, maintain transmission ratios below 8:1, and operate at chain speeds ≤ 15 m/s, effectively meeting diverse agricultural mechanization demands [37]. The transmission system of the *Codonopsis pilosula* mulch-laying and transplanting machine is shown in Figure 11. The machine mainly adopts chain drive, while the power from the ground wheel is transmitted to the intermediate shaft through chain drive. When the intermediate shaft drives the chain plate conveying seedling device, the power input shaft of the chain plate conveying seedling device drives the rotation of the seedling conveying chain plate, thereby completing the transplanting operation. The gearbox transmits power to the sprocket through the power output shaft, and the sprocket transmits power to the rotary tillage and covering device through the intermediate shaft using chain drive. Due to the large distance between the gearbox output and the rotary tillage and covering shaft, as well as the ground wheel shaft and the seedling conveying device, the center distance of the chain drive becomes too large, resulting in excessive sag and vibration, which reduces the transmission efficiency. To solve this problem, an intermediate shaft is designed and installed on the frame to transmit the power from the gearbox output to the rotary tillage and covering device through the intermediate shaft [38]. In this way, the power provided by the ground wheel can drive the rotation of the seedling conveying device through the intermediate shaft, thus realizing the functionality of the machine.

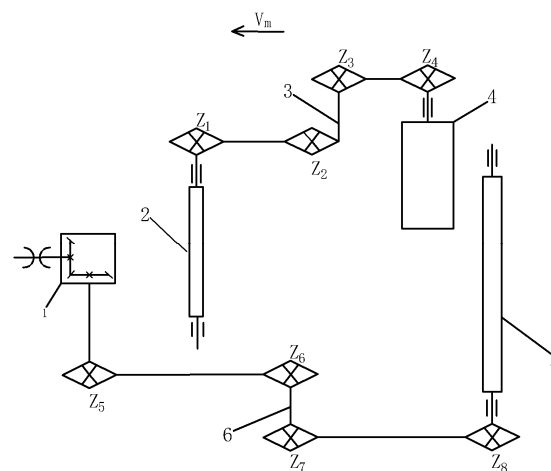


Figure 11. Schematic of the transmission system with 1. Gearbox, 2. Ground wheel shaft, 3. Intermediate shaft, 4. Seedling device, 5. Rotary tillage and covering axis, and 6. Intermediate shaft.

The ground wheel, as the main power source for driving the linear seed supplying mechanism, directly determines the stability of the automatic seed supplying operation based on its reliability. However, the diameter of the ground wheel is a key factor that affects its strength. After final design considerations, the diameter of the ground wheel has been determined as 500 mm.

The rated speed of the engine power output shaft is 540 rpm. When the implement speed is 0.25 m/s, the ground wheel speed of the Dong Fang Hong SG354 tractor in creeper gear is:

$$n = \frac{60v}{2\pi r} \quad (20)$$

where v is the forward speed of the machine, m/s; r is the radius of the ground wheel, mm. From Equation (20), the rotational speed of the ground wheel shaft is 9.5 r/min.

The rotational speeds of the various sprockets in the chain drive are calculated according to the following formula:

$$\frac{n_z}{n_c} = \frac{Z_c}{Z_z} \quad (21)$$

where n_z is the rotational speed of the master wheel, r/min; n_c is the rotational speed of the driven wheel, r/min; Z_z is the number of teeth of the master sprocket; Z_c is the number of teeth of the driven sprocket.

Among them, the active sprocket connected to the ground wheel is selected with 26 teeth, the driven sprocket is selected with 15 teeth, the transitional sprocket is selected with 42 teeth, the driving sprocket of the seedling-supplying mechanism is selected with 12 teeth, the sprocket on the output shaft of the gearbox is selected with 10 teeth, the sprocket on the input shaft of the intermediate shaft is selected with 15 teeth, the sprocket on the intermediate shaft that matches the rotary tillage and covering device is also selected with 15 teeth, and the sprocket that drives the rotary tillage and covering device is also selected with 15 teeth. Based on the selected number of teeth and the speed of the power output shaft, the rotational speed of the driving shaft of the machine for the seedling supplying mechanism is calculated as 20.6 r/min, and the rotational speed of the active shaft of the rotary tillage and covering device is calculated as 360 r/min. Given the rotational speed of the driving shaft, the linear velocity of the seedling conveying chain plate can be calculated using the following formula:

$$v_s = n_z \times 2\pi r_z \quad (22)$$

where v_s is the linear speed of the seedling transporting chain plate, mm/min; r_z is the radius of the active wheel, mm;

Among them, the radius of the active wheel of the seedling-transporting chain plate is 40 mm, and then the linear speed of the seedling-transporting chain plate is 0.09 m/s.

To ensure the smooth process of seedling delivery during the transportation of *Codonopsis* seedlings on the seedling conveying chain plate, it is necessary to ensure that the forward speed of the machine is greater than the linear velocity of the seedling conveying chain plate. Based on the previous calculations, the linear velocity of the seedling conveying chain plate for the *Codonopsis* transplanter is determined to be 0.09 m/s, while the speed of the tractor's crawler gear is 0.25 m/s. By calculating, it can be confirmed that the seedling conveying chain plate meets the transport requirements.

4. Field Experiment

4.1. Experimental Condition

The field test was carried out on 20 May 2023 at the test site of Dingxi City Sanniu Agricultural Machinery Manufacturing Corporation Chan Kou Town, Dingxi City, Gansu Province (as shown in Figure 12). The length of the test plot should be not less than 20 m, the preparation area at both ends should be not less than 10 m, and the width should meet the test requirements. The condition of the test plot was adjusted, and the method of soil preparation and soil texture were recorded; finally, the length of the test plot was determined as 40 m, the width as 10 m, and the soil texture as sandy loam. The average value of soil water content was 14.53%, and soil capacity was 1.128 g/cm³, which met the requirements of "T/NJ 1207–2020 Roots and Stems Chinese herbal medicine transplanting machine" for transplanting test soil. The seedlings of *Codonopsis pilosula* were taken from the locally grown white-striped *Codonopsis pilosula*, with an average seedling length of 200 mm and a seedling diameter of about 3 mm.



Figure 12. Field test: (a) machine setup and (b) result assessment.

4.2. Experimental Test and Methodology

The transplanting machine of *Codonopsis pilosula* was powered by a Dong Fang Hong SG354 tractor with a power of 25.7 kW. The transplanting machine was towed by the three-point hitch, and the operating speed was controlled at 0.25 m/s. Two hundred plants were measured per plot, and 17 repeated field experiments were conducted on the transplanter according to the above operating conditions. Theoretically, the transplanting spacing of *Codonopsis pilosula* seedlings was 40 mm, the planting angle was 25° , and the planting depth was 50 mm. The transplanting efficiency (number of plants transplanted per unit of time) is an important parameter for evaluating the performance of transplanting machines. The assessment of transplanting quality mainly includes the plant spacing qualification rate and the planting depth qualification rate. Therefore, the plant spacing qualification rate and the planting depth qualification rate are selected to comprehensively evaluate the plant spacing accuracy and planting depth of the *Codonopsis pilosula* film covered exposed transplanting machine. The levels of the experimental factors are shown in Table 4.

Table 4. Test factors and levels.

Levels	Machine Forward Speed $X_1/(\text{m} \cdot \text{s}^{-1})$	Speed of the Seedling Chain $X_2/(\text{m} \cdot \text{s}^{-1})$	Embedded Depth X_3/mm
−1	0.25	0.09	45
0	0.3	0.11	50
1	0.35	0.13	55

According to the relevant experimental methods for transplanting machinery in the Mechanical Industry Standard of the People's Republic of China T/NJ 1207-2020, performance tests are conducted with tractor forward speeds of 0.25 m/s, 0.3 m/s, and 0.35 m/s. The average forward speed of the machine is maintained at the specified test speed. After each test, measurements are taken over five segments, each with a continuous length of no less than 5 m. A planting depth between 50 and 60 mm is considered qualified, and a plant spacing between 40 and 50 mm is considered qualified. The qualification rates for planting depth (Y_1) and plant spacing (Y_2) are calculated as follows:

1. Pass rate for planting depth

After covering the rhizomatous medicinal materials with soil, carefully remove the soil cover in each small area to measure the thickness of the soil covering the seedling emergence point. The requirement for the qualified planting depth rate is $\geq 80\%$. The qualified planting depth rate is calculated using the following formula.

$$H = \frac{H_h}{H_z} \times 100\% \quad (23)$$

Formal:

H —Planting depth pass rate; in percent (%);

H_h —The sum of the number of eligible planting depths in each plot, in units of;

H_z —Total number of plants measured in each plot, in pieces.

2. Pass rate for spacing

Measure the distance between adjacent seedling heads within each small area. The requirement for the qualified plant spacing rate for seedling planting is $\geq 80\%$. The qualified plant spacing rate is calculated using the following formula:

$$J = \frac{J_h}{J_z} \times 100\% \quad (24)$$

Formal:

J —Plant spacing qualified rate; the unit is a percentage (%);

J_h —Sum of qualified number of plant spacings of each cell, unit is each;

J_z —The total number of plant spacings was measured in each plot, and the unit was one.

4.3. Analysis of Experimental Results

4.3.1. Experimental Results

The three-factor, three-level experimental design includes 17 test groups (5 groups for zero-point estimation errors and 12 groups for analyzing factors). The experimental design and results are shown in Table 5.

Table 5. Results of field experiments.

Serial Number	X_1	X_2	X_2	Y_1	Y_2
1	−1	1	0	95	83.3
2	0	−1	−1	88.3	93.3
3	0	1	−1	85	90
4	1	0	−1	83.3	86.7
5	1	−1	0	90	81.7
6	0	0	0	96.7	90
7	0	0	0	95	90
8	0	0	0	95	88.3
9	−1	0	1	88.3	96.7
10	0	1	1	90	93.3
11	0	0	0	96.7	90
12	0	−1	1	90	96.7
13	1	1	0	93.3	81.7
14	−1	−1	0	96.7	93.3
15	0	0	0	95	90
16	−1	0	−1	86.7	93.3
17	1	0	1	83.3	88.3

4.3.2. Regression Equation Building and Analysis

Using Design-Expert, a variance analysis of the regression model for planting depth qualification rate (Y_1) and plant spacing qualification rate (Y_2) was conducted, as shown in Tables 6 and 7.

Table 6. Analysis of Variance (ANOVA) table for the planting depth compliance model.

Test Indicators	Source of Variation	Square Sum	Degrees of Freedom	Mean Square	F	p
Planting depth pass rate	model	347.59	9	38.62	27.81	0.0001 **
	X_1	35.28	1	35.28	25.41	0.0015 **
	X_2	0.3612	1	0.3612	0.2601	0.6257
	X_3	8.61	1	8.61	6.20	0.0416 *
	X_1X_2	6.25	1	6.25	4.50	0.0716
	X_1X_3	0.6400	1	0.6400	0.4609	0.5190
	X_2X_3	2.72	1	2.72	1.96	0.2042
	X_1^2	24.81	1	24.81	17.87	0.0039 **
	X_2^2	1.04	1	1.04	0.7505	0.4150
	X_3^2	259.63	1	259.63	186.97	<0.0001 **
	residual	9.72	7	1.39		
	incoherent	6.25	3	2.08	2.40	0.2080
	inaccuracy	3.47	4	0.8670		
	aggregate	357.31	16			

* Indicates that the difference is significant. ($p \leq 0.05$); ** Indicates that the difference is highly significant. ($p \leq 0.01$).

Table 7. Analysis of Variance (ANOVA) table for the model of plant spacing pass rate.

Test Indicators	Source of Variation	Square Sum	Degrees of Freedom	Mean Square	F	p
Spacing pass rate	Model	327.56	9	36.40	57.39	<0.0001 **
	X_1	99.40	1	99.40	156.74	<0.0001 **
	X_2	34.86	1	34.86	54.97	0.0001 **
	X_3	17.11	1	17.11	26.98	0.0013 **
	X_1X_2	25.00	1	25.00	39.42	0.0004 **
	X_1X_3	0.8100	1	0.8100	1.28	0.2957
	X_2X_3	0.0025	1	0.0025	0.0039	0.9517
	X_1^2	47.75	1	47.75	75.29	<0.0001 **
	X_2^2	7.03	1	7.03	11.09	0.0126
	X_3^2	103.48	1	103.48	163.16	<0.0001 **
	residual	4.44	7	0.6342		
	incoherent	2.13	3	0.7092	1.23	0.4091
	inaccuracy	2.31	4	0.5780		
	aggregate	332.00	16			

** Indicates that the difference is highly significant. ($p \leq 0.01$).

By substituting the obtained relevant parameters into the equation, the regression models for planting depth qualification rate and plant spacing qualification rate are as follows:

$$Y_1 = 95.68 - 2.10X_1 - 0.2125X_2 + 1.04X_3 + 1.25X_1X_2 - 0.4X_1X_3 + 0.825X_2X_3 - 2.43X_1^2 + 0.4975X_2^2 - 7.85X_3^2 \quad (25)$$

$$Y_2 = 89.66 - 3.52X_1 - 2.09X_2 + 1.46X_3 + 2.50X_1X_2 - 0.45X_1X_3 - 0.025X_2X_3 - 3.37X_1^2 - 1.29X_2^2 + 4.96X_3^2 \quad (26)$$

As shown in Table 6, the planting depth qualification rate model has $p < 0.01$, indicating that the regression model is highly significant; the lack-of-fit term has $p > 0.05$, suggesting that the lack of fit is not significant, meaning that the quadratic regression equation fitted by the model aligns well with the actual data and can correctly reflect the relationship between the planting depth qualification rate Y_1 , X_1 , X_2 , and X_3 . The regression model can effectively predict various experimental results in the optimization experiment. Among the terms in the model, the linear term X_1 has an extremely significant impact, the quadratic terms X_1^2 and X_3^2 have an extremely significant impact, X_3 has a significant impact, and the other terms are not significant. Based on the size of the regression coefficients of each factor in the model, the order of influence on the planting depth qualification rate is X_1 , X_3 , and X_2 .

The model for the plant spacing qualification rate, as shown in Table 7, has a p -value of less than 0.0001, indicating that the regression model is highly significant. The lack-of-fit term has a p -value > 0.05 , suggesting that the lack of fit is not significant, meaning the quadratic regression equation fitted by the model aligns well with the actual data. It accurately reflects the relationship between the plant spacing qualification rate Y_2 and the variables X_1 , X_2 , and X_3 . The regression model can predict the results of various experiments in the optimization process with good accuracy. Among the terms, the linear terms X_1 , X_2 , and X_3 are highly significant, the quadratic terms X_1^2 and X_3^2 are highly significant, and the interaction term X_1X_2 is significant, while the other terms are not significant.

The response surface plots for the relationships between the factors are generated based on the regression models, respectively.

As shown in Figure 13a, when the chain speed is at the medium level and the planting depth is fixed at a certain value, the qualification rate of planting depth decreases as the machine forward speed increases. This is because when the machine moves too quickly, the time for the soil covering device to operate is reduced, which leads to a decrease in the amount of soil covered, affecting the qualification rate of planting depth. When the machine's forward speed remains constant, the qualification rate of planting depth first increases and then decreases as the soil entry depth increases. This is because when the entry depth of the seed bed preparation device is small, the planting of the *Codonopsis* is too shallow. However, when the entry depth is too large, the planting becomes too deep, both of which result in a decline in the qualification rate of planting depth.

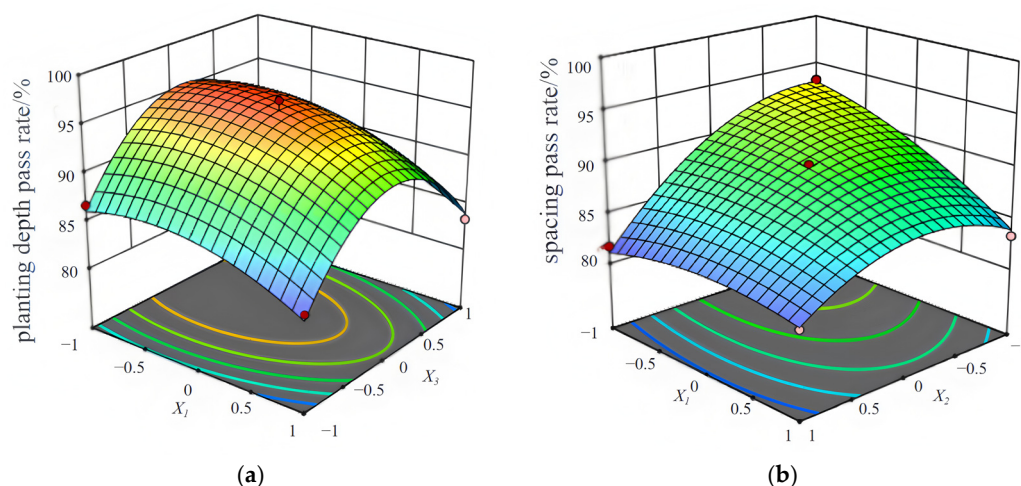


Figure 13. Impact of different combinations of factors on indicators: (a) $Y_1 = f(X_1, X_3)$; (b) $Y_2 = f(X_1, X_2)$.

As shown in Figure 13b, the qualification rate of planting depth decreases as the machine forward speed and chain speed increase. The main reason for this phenomenon is

that when the machine and chain speeds are too fast, the *Codonopsis* seedlings, which are relatively long, get scraped by the chain at high speeds. This causes the seedlings to shift or tilt, leading to a decrease in the qualification rate of plant spacing.

The number of *Codonopsis* seedlings planted after the experiment was counted by selecting five 1 m² plots, with the number of seedlings in each plot being 44, 48, 40, 51, and 47, respectively. The average number of seedlings, 46, was taken for estimation. Therefore, the planting density of *Codonopsis* seedlings for this membrane-covered head-out transplanting machine design is 30,668 plants per acre. The *Codonopsis pilosula* mulching and transplanting machine can complete 0.2 hm² per day after 10 h of operation, and the cost of transplanting 1 hectare is roughly estimated to be 3280 RMB. Labor costs per hectare are approximately 7200 RMB, as 10 people can complete 0.18 hectares of land with a daily labor of 10 h. Each worker costs 130 yuan per day, resulting in a cost savings of 3920 RMB compared to manual labor. Using artificial cultivation, each person can only work 0.018 hm² per day (calculated as 10 h), while using machinery (with manual assistance), each person can work 0.04 hm² per day. The efficiency of mechanical operation is 2.2 times that of manual operation [37]. The *Codonopsis* membrane-covered head-out transplanting machine in this design meets the national and industry standards for plant spacing qualification rate and planting depth qualification rate, as determined by field experiments. During operation, all components function smoothly without any failures, demonstrating high reliability.

5. Discussion and Conclusions

Based on the current situation of *Codonopsis* transplantation in the arid region of Northwest China, the *Codonopsis pilosula* outcrop film-laying and transplanting machine was designed.

The design of key components of the machinery was carried out, including the structure and related parameters of the seed bed preparator, seedling planting device, soil covering device, and transmission system, which ensures the proper transplanting of *Codonopsis* seedlings, and the intended working process was achieved.

Based on discrete element simulation, the optimized design of the soil entry angle for the seed bed preparation device ensures the stability of the trench depth; the swing mechanism achieves precise adjustment of row spacing, and the synchronous control mechanism between the seedling transport chain plate and the machine travel speed achieves the qualified rate of plant spacing and planting depth.

Field experiment results indicate that at forward speeds of 0.20, 0.25, and 0.3 m/s, the average qualified rate of planting depth is 91.08%, and the average qualified rate of plant spacing is 89.8%. The experimental results meet the design requirements, demonstrating that the machine can accomplish the entire operation process of seed bed preparation, seedling placement, rotary tillage, mulching, and soil covering in one go. These field performance indicators meet both national and industry requirements.

The mechanized outcrop cultivation technology of traditional Chinese medicine not only solves the problems of high machine power consumption and root and stem loss rate but also effectively solves the problem of increased soil resistance caused by deep excavation in the harvesting process, making it suitable for large-scale promotion in hilly and mountainous areas. In the future, key technologies such as automatic separation of seedlings and automated seedling placement need to be gradually developed to ensure the plant spacing, row spacing, and depth indicators for seedling transplantation and to improve the comprehensive mechanization level.

Author Contributions: Conceptualization, W.S. and M.Z.; software, J.B., J.W. and P.A.S.; investigation, J.B., W.S., M.Z. and L.Z.; resources, W.S., J.W. and P.A.S.; writing—original draft preparation, J.B.;

writing—review and editing, W.S., P.A.S., M.Z., L.Z. and J.B.; supervision, M.Z., L.Z., J.W. and P.A.S.; project administration, W.S.; funding acquisition, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Central-Guided Local Science and Technology Development Fund Project (25ZYJA036), the Gansu Province Agricultural Machinery Equipment Shortcomings Action Project (njyf2024-03-1), and the Gansu Provincial University Industry Support Plan (2022CYZC-42).

Data Availability Statement: Data are reported within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

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