Development and Validation of a Potato Seeding Machine with Integrated Plastic Film Mulch Punching Mechanism

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Abstract: A seeding machine for planting potatoes in double rows on large ridges in the cold and arid regions of northwest China was designed and built at Gansu Agricultural University. The machine is capable of achieving the integrated operations of ridge formation, mulching, hole punching, and the precise covering of holes on the film. The key components were analyzed and designed, and the link lengths of the crank film-piercing and hole-punching mechanism were refined using MATLAB R2022a software. The structures and working parameters of the film-piercing and hole-punching mechanism, the dual-opening punching and seeding mechanism, the ridge-forming and soil-covering mechanism, and the seed-casting device were designed. The dynamics of the ridge-forming and soil-covering were simulated using the discrete element method to capture the effects of different machine parameters on the soil covering operation. Field tests showed that the full soil-covering rate of film holes, the qualified rate of hole spacing, the hole misalignment rate, the degree of damage to the light-receiving surface of the film, and the qualified rate of sowing depth under the film were 94.8%, 87.6%, 4.3%, 33.4%, and 95.6%, respectively. These indicators met the requirements of industry standards, and the test results met the design and actual operation requirements, enabling the integrated operations of ridge formation, mulching, hole punching, sowing on the film, and the accurate soil covering of the holes.

Keywords: potato film mulching; potato seeding; holes punching; hole covering; discrete element method

1. Introduction

Potatoes, as a versatile crop, have great potential for increasing planting areas and yields [1,2]. In 2015, China initiated a strategy to make potatoes a staple food, providing guidance for the development of the potato industry. The unique geographical environment and climate conditions in the northwest region are highly suitable for potato growth, playing an important role in promoting farmers’ incomes and regional economic development [3–5]. In this region, potato planting often employs full film-covering technology for drought resistance. This method features moisture retention, water conservation, fertilization retention, and yield improvement, making it one of the main technologies for increasing potato yield and income in the cold and arid areas of the northwest [6,7]. The planting methods mainly include planting before film covering and planting after film covering [8]. The former method requires manually tearing the film to release the seedlings after emergence, or covering the seed row with soil according to agronomic techniques to allow for natural emergence. This can lead to issues such as time-consuming and labor-intensive manual seedling release, seedling burning, or soil compaction in the planting rows, resulting in a poor seedling emergence rate if not carried out in a timely manner. The latter planting model, which involves covering the film after planting, is more suitable...
for the agronomic requirements of potato cultivation under film in the northwest region. However, this method lacks mature equipment for hole-punching and seeding on the film, necessitating manual hole-punching and covering. This can result in an inadequate covering of the holes, exacerbating soil moisture loss and causing the film to be blown off by strong spring winds [9].

At present, the film-piercing seeding device is only suitable for the mechanized planting of corn, soybeans, cotton and other small grains of shallow crops. Fornstrom et al. [10] designed a hole-sowing wheel with a conical hole-former to achieve the precision hole-sowing of sugar beet. Heinemann et al. [11] developed a pneumatic drilling planter, which consists of a pneumatic plunger-type hole-former and a seed dispenser. In recent years, planting using mechanized film mulching technology in China has become increasingly mature and has been applied to the mechanized planting of crops such as corn, wheat, peanuts, and cotton, using developed roller-type, inline-type, and rotary-type hole-forming mechanisms [12–16].

However, achieving the best yield for potato planting requires a planting depth of 10 to 15 cm and small film holes after punching and sowing. It is also necessary to cover the holes with soil to prevent soil moisture loss and to stop the wind from lifting the film. The hole-punching process should have a large vertical displacement and a small horizontal displacement to avoid tearing or lifting the film, and the holes need to be covered with soil after planting. Research on planting using mechanized film mulching, both domestically and internationally, mainly focuses on small-seeded crops such as vegetables and grains, with less emphasis on meeting the requirements for mechanized planting using potato film mulching [17]. The development of equipment for the mechanized planting of potatoes under film mulching is an urgent need in potato production in the northwest region.

This paper aims to achieve the mechanized planting of potatoes on mulch. A potato seeding machine, featuring hole punching and soil covering on the film, was designed with optimized components. These components include the film-piercing and hole-punching mechanism, the dual-opening punching and seeding mechanism, the ridge-forming and soil-covering mechanism, and the seed-casting device. The rod length parameter of the hole-punching mechanism was optimized using MATLAB R2022A software. The working process of the ridge-forming and soil-covering mechanism was simulated through the discrete element method to determine the optimal design parameters. A field test was conducted to validate the working state of the entire machine.

2. Materials and Methods

2.1. Agronomic Requirements

Figure 1 shows a schematic diagram of ridge double-row hole sowing and soil covering for planting potatoes in the hilly and mountainous areas of northwest China. The ridge height is 150–200 mm, with a width of 900 mm, and it is covered with a 1200 mm plastic film. Seeds are sown by punching holes in the film, with potato seedlings arranged in double rows on the ridge to allow for ventilation and light transmission. Sowing depth is 130 mm, plant spacing is 350 mm, and row spacing is 400 mm. After sowing, a 30–50 mm layer of soil covers the planting holes to prevent the film from being blown off by strong winds and to reduce soil moisture loss.

2.2. Overall Structure

As shown in Figure 2, the potato seeding machine with integrated plastic film mulch punching mechanism mainly comprises a frame, a straddling ridge-forming and soil-conveying device, a film-covering device, a film-piercing and hole-punching mechanism, a hole-covering device, a seed-casting device, and a transmission system.

2.3. Working Principle

During operation, the seeder connects to the tractor’s three-point suspension frame via a hanging mechanism. The transmission system links to the tractor’s power output
shaft through a universal joint drive shaft, delivering power to several components: the ridge-forming and soil-conveying device, the film-piercing and hole-punching mechanism, and the seed-casting device.

![Figure 1. Schematic diagram of double-row hole sowing and soil covering in large ridges of potatoes.](image)

As the seeder moves forward under the tractor’s traction, the ridge-forming and soil-conveying device begins its operation. The soil shovel breaks the soil while the scraper conveyor chain transports it backward to the film edge and hole-covering device. This process forms ridge furrows where the soil shovel operates, creating larger ridges centrally. The film-covering device then places plastic film over the large ridges. When the film-piercing and hole-punching mechanism positions the hole-making and seed-dropping device at its highest point, the seed-casting device deposits potato seeds into it. As the hole-making and seed-dropping device reaches planting depth, its opening and closing mechanism releases the seeds into the prepared holes. The hole-covering device subsequently fills these holes with the soil it receives, completing the covering operation.

3. Results and Discussion

3.1. Film-Piercing and Hole-Punching Mechanism

The film-piercing and hole-punching mechanism pierces the plastic film and punches holes. A pair of these assemblies operate on both sides of the unit, spaced 400 mm apart to meet row spacing requirements. To achieve ventilation between plants and to minimize
transmission loading, the two piercing mechanisms operate synchronously but at a phase difference of 180 degrees [18].

As shown in Figure 3, the film-piercing and hole-punching mechanism consists of a fixed plate, driving and driven sprockets, a tensioning sprocket, a crank, a connecting rod, a punching and seeding connecting rod, and a dual-opening punching and seeding mechanism. The drive shaft connects to the power output shaft of reducer B through a chain coupling.

During operation, the output power of reducer B drives the driving sprocket, rotating it, which in turn rotates the driven sprocket via chain transmission. This rotation drives the crank, connecting rod, and punching and seeding connecting rod, causing the punching mechanism to break the film and create holes.

Figure 4 shows a schematic diagram of the film-piercing and hole-punching mechanism, where OC and AB are cranks, CD and BD are connecting rods, and the two ends of connecting rod BD are, respectively, hinged with crank AB and the hole-punching and sowing connecting rod CD. The hole-punching and sowing mechanism EF is installed on the hole-punching and sowing connecting rod CD. The OXY rectangular coordinate system has O as the origin, the horizontal direction as the x-axis, and the vertical direction as the y-axis. Relative to this coordinate system, the trajectory of the seeding device point F is given by the following equation [19–21].

\[
\begin{align*}
  x_F &= l_2\cos\alpha_2 + l_3\cos\alpha_3 + l_4\cos\alpha_4 + l_5\sin\alpha_3 \\
  y_F &= -l_2\sin\alpha_2 + l_3\sin\alpha_3 + l_4\sin\alpha_4 - l_5\cos\alpha_3
\end{align*}
\] (1)

According to Formula (1), the parameters of the film-piercing and hole-punching mechanism affect the displacement and velocity of point F of the seeder. To optimize the design of this mechanism, parameter optimization is conducted using MATLAB R2022a.
software based on the kinematic model. The MATLAB application interface, depicted in Figure 5, includes sections for mechanism parameter settings, calculation–result display, and image representation. By inputting the necessary mechanism parameters, the planting trajectory corresponding to point F of the seeder, along with its horizontal and vertical velocities, can be determined.

**Figure 4.** Kinematic diagram of the film-piercing and hole-punching mechanism, where F the tip of the seeder visible in Figure 3.

**Figure 5.** MATLAB application interface.
To facilitate the study of the influence of parameters on the motion characteristics of the hole-punching and sowing mechanism, and to narrow down their range, the parameters of the mechanism are first constrained according to the characteristics of the mechanism itself, the overall structure and the design requirements.

According to the requirements of the overall machine design, to meet the overall coordination of the unit, the installation positions of point O and point A are determined. The measured fixed dimensional parameters are $l_0 = 300 \text{ mm}$ and $\alpha_1 = 45^\circ$. The length of the seeder is set to $l_5 = 220 \text{ mm}$.

According to the agronomic requirements for potato planting, the forward speed of the machine is set to 1.746 km/h, with a frequency of 85 stalks a row per minute, that is, the designed planting row spacing is 350 mm.

According to the design requirements and mechanism constraints, the initial values are selected as $l_1 = 100 \text{ mm}$, $l_2 = 70 \text{ mm}$, $l_3 = 220 \text{ mm}$, $l_4 = 270 \text{ mm}$, $l_6 = 190 \text{ mm}$, $\omega = 9 \text{ rad/s}$, and the upper crank AB and lower crank OC are always kept parallel. Based on the MATLAB R2022a software, the control variable method is applied to select three arithmetic progression numbers to conduct a single-factor analysis on the sowing trajectory, vertical speed and horizontal speed of the point F.

The trajectory of point F shown in Figure 6 resembles the Greek letter $\gamma$. With the increase in the length of upper crank AB($l_1$), the trajectory of point F is elongated vertically, the amplitude of the up and down movement of the planting duckbill increases, the position of the trajectory intersection point remains almost unchanged, the offset of the buried part increases, and the planting depth increases; with the increase in the length of the lower crank OC($l_2$), the trajectory of point F is “compressed”, the vertical movement amplitude decreases, the position of the trajectory intersection point approaches the ridge line, the horizontal displacement around the lower part of the trajectory, subsequently referred to as “button”, increases accordingly, and the displacement between the trajectory intersection point and the lowest point increases; with the increase in the length of the connecting rod CD($l_3$), the horizontal displacement around the button decreases, and the displacement between the trajectory intersection point and the lowest point decreases; with the increase in the length of the extending part DE of the connecting rod CD($l_4$), the trajectory as a whole shifts slightly, and the highest point rises, with very little impact on the other parameters, which can be almost ignored; with the increase in the length of the connecting rod BD($l_6$), the trajectory as a whole shifts downward; with the increase in the angular velocity ($\omega$), the position of the trajectory intersection point moves upward, the horizontal displacement around the button increases accordingly, and the planting row spacing decreases.

It is easy to see that the horizontal displacement of the rotary button affects the size of the hole. The larger the horizontal displacement of the rotary button, the greater the soil disturbance caused by the planting duckbill, and the more severe the hole damage. The displacement of the trajectory intersection and the lowest point affects the drilling depth. The larger the displacement, the deeper the hole when the hole size is constant. The soil entry offset determines the degree of misalignment between the sowing point and the center of the hole. The larger the soil entry offset, the greater the horizontal distance between the sowing point and the center of the hole, and the more serious the misalignment of the planting hole.

Similarly, research on the effects of various parameters on the vertical and horizontal velocity components of the point F is conducted. To achieve smooth seeding, when the sowing trajectory is at the highest and lowest points in the vertical direction (seeding point and sowing point), the vertical velocity component of point F is zero and the acceleration is maximum; according to the principle of “zero-speed planting”, the horizontal velocity component of point F should be equal in magnitude but opposite in direction to the forward speed of the unit, which can effectively avoid film tearing and lifting by the seeder [22].

The optimization of parameters for the mechanism of film-piercing and hole-punching is complex with multiple parameters and objectives. Changes in each parameter will affect the performance of the mechanism. By using the method of successive approximation [23],
considering the influence of sowing trajectory, inoculation, speed during sowing process, and the impact of “zero-speed planting”, the following set of optimized parameters has been obtained:

\[ l_1 = 100 \text{ mm}, \ l_2 = 100 \text{ mm}, \ l_3 = 200 \text{ mm}, \ l_4 = 270 \text{ mm}, \ l_6 = 190 \text{ mm}, \ \omega = 9 \text{ rad/s} \]

As shown in Figure 7, the plant spacing basically meets the agronomic requirements. When the point F moves to the ridge line, the horizontal velocity is \(-0.407 \text{ m/s}\), which is opposite to the direction of the unit’s forward speed and close in magnitude, largely avoiding the occurrence of film tearing and lifting. When the point F moves to the highest and lowest points (inoculation point and sowing point), the vertical velocity is close to zero, thus meeting the design requirements.

![Figure 6](image_url)

**Figure 6.** Effect of link lengths \(l_1, l_2, l_3, l_4, l_6\) and of rotational speed \(\omega\), upon the trajectory of point F.

### 3.2. Dual-Opening Punching and Seeding Mechanism

During the operation of the whole machine, the dual-opening punching and seeding mechanism is responsible for receiving potato seeds, punching holes on the film and depositing potato seeds. The common way to open the seed dropping mouth is semi-open, with half of the seed dropping mechanism fixed on the seed dropping wheel as a fixed door, and the other half as a movable door hinged to the fixed door. The seed dropping mouth is opened by the gravity of the seed dropping wheel compressing the spring or by a built-in cam mechanism. After the seed dropping mouth is opened, if the turning radius of the planting point is greater than the turning radius of the outer edge of the movable door by more than the size of the seed, the emergence of the movable door will disturb the ejected seeds. Therefore, this seed dropping method is not suitable for planting potato seeds with larger sizes [24–27].

To avoid the demerits of the half-open type, a dual-opening punching and seeding mechanism is designed, the structure of which is shown in Figure 8. It consists of a hole-making and seed-dropping device, an inoculation cup, a pre-tension spring, opening pull wires, opening pull rods, camshafts, rocker arm, etc., where the opening pull wires A and B are integrated. During operation, the film-piercing and hole-punching mechanism moves the seed-dropping mechanism to the top, potato seeds are placed into the inoculation cup, and the seed potatoes in the cup fall into the hole-making and seed-dropping device due to
their own gravity. At this time, the hole-making and seed-dropping device transports the potato seeds. When the hole-making and seed-dropping device carrying the potato seeds moves to the bottom through the mechanism, the operation of breaking the ground film, the soil, and planting the potato seeds is completed through the opening and closing actions.

![Figure 7. Plots of the trajectory and of the x and y components of the velocity of point F after optimization.](image)

**Figure 7.** Plots of the trajectory and of the x and y components of the velocity of point F after optimization.

![Figure 8. The dual-opening punching and seeding mechanism: 1. Inoculation cup. 2. Opening pull rods. 3. Hole-making and seed-dropping device. 4. Pre-tension spring. 5. Camshafts. 6. Rocker arm.](image)

**Figure 8.** The dual-opening punching and seeding mechanism: 1. Inoculation cup. 2. Opening pull rods. 3. Hole-making and seed-dropping device. 4. Pre-tension spring. 5. Camshafts. 6. Rocker arm.

The size of the inoculation cup and the hole-making and seed dropping device is determined by the size of the potato seed, with the average size of cut potatoes being 56.4 mm × 44.3 mm × 31.8 mm [28]. To ensure smooth inoculation, the top of the inocu-
lation cup is designed to be a rectangle with dimensions of 260 mm × 150 mm and the bottom is designed as a circle with the same diameter as the seed hole at the top of the hole-making and seed dropping device, taking a diameter of 100 mm. The hole-making and seed dropping device is designed to be 180 mm in length to ensure that the potato seeds can fall smoothly from the seeder during sowing, with a linear motion distance of 18 mm from fully open to closed.

The opening and closing of the hole-making and seed-dropping device is completed by the coordination of the cam and the rocker arm. When the cam rotates to the far rest angle, the rocker arm pulls the opening pull line, which in turn drives the opening pull rod to open the hole-making and seed-dropping device. After sowing is completed, the cam rotates to the near rest angle, and the hole-making and seed-dropping device closes under the action of the pre-tension spring. When the film-piercing and hole-punching mechanism punches a hole once, the hole-making and seed-dropping device would also open once. When passing through the lowest point, the hole-making and seed-dropping device needs to open quickly to ensure that the potato seeds fall into the lowest part of the furrow hole. After that, it needs to remain open until it leaves the soil and then slowly close to prevent stirring or bringing back the potato seeds. Therefore, the far rest angle of the cam is about 120 degrees. According to the design requirements, the eccentric distance $e$ (i.e., eccentricity radius) of the cam is as follows:

$$e = r + \frac{q s}{q}$$

In the formula, $r$ represents the radius of the cam’s base circle, taken as 33 mm; $q$ represents the distance from the center of the rocker arm shaft to the fixed point of the opening pull line, taken as 188 mm, and $q'$ represents the distance from the center of the rocker arm shaft to the center of the roller, taken as 133 mm.

3.3. The Ridge-Forming and Soil-Covering Mechanism

According to the agronomic requirements for potato cultivation in the northwest region, it is necessary to ridge and mulch before planting. At the same time, in order to prevent soil moisture loss and film tearing by strong spring winds, the edges of the film must be covered with soil, and the holes in the film need to be sealed. The function of the ridge-forming and soil-covering mechanism is to complete the tasks of ridging, covering the edges of the film with soil, and sealing the holes in the film in one go.

Figure 9 shows a schematic diagram of the ridge-forming and soil-covering mechanism, which is composed of a straddling ridge-forming and soil-conveying device and a hole-covering device. To ensure the ridge height, the straddling ridge-forming and soil-conveying device is set to a depth of 150 mm according to the agronomic requirements for potato planting. During operation, the machine moves forward, driving the straddling ridge-forming and soil-conveying device to excavate the soil and transport it backwards to form ridges on both sides, with a large ridge in the middle at a height of 150 mm. At the same time, the film-covering device covers the large ridge with plastic film. Due to the high speed of the straddling ridge-forming and soil-conveying device ($n = 6 \text{ r/s}$), the soil thrown backward is relatively scattered, with some being intercepted by the hole covering device to seal the holes, and some scattered to the edge of the film for edge covering.

3.3.1. Straddling Ridge-Forming and Soil-Conveying Device

In order to achieve the task of digging furrows, forming ridges and transporting soil backwards, improvements have been made to the scraper-lifting belt-type soil-covering device developed by our team. The lifting belt of the device has been changed to a lifting chain, solving the problems of the high precision requirements for processing and the assembly and the “deviation” of the conveyor belt [29]. As shown in Figure 10, the straddling ridge-forming and soil-conveying device consists of a soil-lifting shovel, a scraper board, a lifting chain, driven wheel, a depth adjuster of the soil lifting shovel, a tension device for the lifting chain, a driving wheel, etc.
The ridge-forming and soil-covering mechanism is to complete the tasks of ridge forming and soil transport at the same time. The film covering device covers the large ridge with plastic film. Due to the high speed of the straddling ridge-forming and soil-conveying device, the holes in the film are intercepted by the cover, and the film must be sealed to prevent soil moisture loss and film tearing by strong spring winds. The edges of the film with soil are sealed in one go.

Figure 9 shows a schematic diagram of the ridge-forming and soil-conveying device. To ensure the ridge height, the straddling ridge-forming and soil-conveying device is set to a depth of 150 mm according to the agronomic requirements for potato planting. During operation, the machine moves forward, driving the straddling ridge-forming and soil-conveying device to excavate the soil and transport it backward, improving the scraper 3.0 developed by our team. The lifting belt of the device has been changed to a lifting chain, solving the problems of the high precision requirements for processing and the asymmetry of the conveyor belt assembly and the “deviation” of the conveyor belt due to the lifting chain. Improvements have been made to the scraper board, a lifting chain, driven wheel, a depth adjuster of the soil lifting shovel, a tension device for the lifting chain, a d

Figure 10. Straddling ridge-forming and soil-conveying device, (a) is a partial perspective view, and (b) is a schematic diagram: 1. Soil-lifting shovel. 2. Driven wheel. 3. Scraper board. 4. Lifting chain. 5. Film roller. 6. Soil-blocking plate. 7. Driving wheel. 8. Protective cover. 9. Tension device for the lifting chain. 10. Depth adjuster of soil-lifting shovel.

Figure 11 shows the analysis diagram of the motion of the straddling ridge-forming and soil-conveying device. Assuming the forward speed v and chain speed v’ of the unit are stable, and taking the lowest point as the origin to establish a coordinate system, the trajectory equation of the scraper chain’s top point as it rotates around the driven wheel is \[29\]:

\[
x = r \cos(\delta + \gamma) + h, \quad y = r \sin(\delta + \gamma), \quad x' = v't, \quad y' = v't + \frac{v^2}{2a},
\]

where \(a\) is the acceleration of the unit, \(v\) is the forward speed, \(v’\) is the chain speed, \(r\) is the effective radius of the driven wheel, \(\delta\) is the angle of the lifting chain, and \(\gamma\) is the angle of the unit.

\[33\] \(y = h + \frac{v'^2}{2a} - \frac{v^2}{2a} \cos(\delta + \gamma)\]

\[34\] \(x = r \sin(\delta + \gamma) + h \cos(\delta + \gamma) - \frac{v'^2}{2a} \sin(\delta + \gamma)\]

\[35\] \(x' = v't, \quad y' = v't + \frac{v^2}{2a}\)

The ridge-forming and soil-conveying mechanism is a partial perspective view, and Figure 10 shows the analysis diagram of the motion of straddling ridge-forming and soil-conveying device. Assumptions of the forward speed v and chain speed v’ of the unit are stable, and taking the lowest point as the origin to establish a coordinate system, the
trajec- 
tory equation of the scraper chain’s top point as it rotates around the driven wheel is [29]:
\[
\begin{align*}
    x &= \frac{r \delta}{2} + (r + h) \sin \delta \\
    y &= (r + h)(1 - \cos \delta) \\
\end{align*}
\]
\[ -\gamma < \delta < \pi - \gamma \] (3)

Figure 11. Analysis diagram of the motion of straddling ridge-forming and soil-conveying device.

In Equation (3), \( x \) represents the horizontal displacement of the scraper board (mm); \( y \) represents vertical displacement of the scraper board (mm); \( r \) represents radius of the driven wheel (mm); \( h \) represents scraper height (mm); \( i \) represents the ratio of chain speed to the advance speed of the machine; \( \delta \) represents the angle at which the scraper board turns (degree); and \( \gamma \) represents the angle between the scraper chain and the horizontal plane (degree).

The upper surface of the soil on the scraper board is at an angle with the horizontal plane, which is the internal friction angle of the soil \( \psi \). The amount of soil on each scraper is the amount of soil transported by the length of the scraper chain \( d \) (spacing between adjacent scrapers). The volume of soil transported is obtained by multiplying the end surface area by the width of the scraper board. If the forward speed of the unit is \( v \) and the linear speed of the scraper chain is \( v' \), then the amount of soil \( Q \) transported by the unit forward \( d' \) is [29]:

\[
Q = \begin{cases} 
    \frac{\eta bd h^2}{2 \tan(\gamma - \psi)d} & d \geq \frac{h}{\tan(\gamma - \psi)} \\
    \eta bd i \left[ h - \frac{d \tan(\gamma - \psi)}{2} \right] & d < \frac{h}{\tan(\gamma - \psi)} 
\end{cases}
\] (4)

where \( \eta \) represents the conveying efficiency mainly related to the filling coefficient and the slip rate of the scraper chain, and \( b \) represents width of the scraper board, (mm).

To determine the amount of covering soil, a theoretical plant spacing of 350 mm is taken as the subject of study. The width of the soil strip on one side of the film is 100 mm, and the thickness is between 30 and 50 mm, so the volume is \( 1.05 \times 10^{-3} \sim 1.75 \times 10^{-3} \text{m}^3 \).

The length of the film hole is 90 mm. In this design, the width of the soil-turning shell of the hole-covering device is 110 mm, the distance from the soil-turning shell to the ground is small (120 mm), and the forward speed of the unit is low (0.49 m/s). With the cooperation of the soil-blocking plate, the soil forms an approximate conical shape, with a base diameter of about 120 mm on the film surface. The soil in the northwest agricultural area is mainly loess, with an internal friction angle of the surface soil of about 28 degrees, so the volume is \( 0.11 \times 10^{-3} \text{m}^2 \). The hole-making and seed-dropping device is a tetrahedron. During the hole-making process, the seed-dropping mouth is opened, and the hole formed is a wedge-
shaped body with a depth of 100–150 mm. According to the size of the potato seed, the distance from the bottom opening of the seed-dropping mouth is 100 mm. The volume of soil needed to fill the hole is between 680 and 1020 cm$^3$. The straddling ridge-forming and soil-conveying device uses a 16a curved plate chain drive, with a scraper width of 180 mm, a scraper spacing of 50 mm, a scraper height of 30 mm; the ratio of the line speed $v'$ of the curved plate chain to the forward speed $v$ of the unit is 2.69, the angle between the curved plate chain and the horizontal plane is $\gamma = 45^\circ$, and the conveying efficiency is taken as 0.7. When the unit moves forward by 350 mm, the theoretical soil conveying volume $Q$ of the curved plate chain is 2660 cm$^3$, which meets the design requirements.

3.3.2. Hole-Covering Device

Figure 12 shows the structural diagram of the hole-covering device. The hole-covering device is composed of a soil-sliding trough, a soil-turning shell, a soil-turning pull rod, a hinge shaft, a limiting shaft, a pulley, a lifting pull line, a traction rod, and a control rod. The lifting pull lines A and B are integrated, and the working principle of the control rod is consistent with the cam principle.

![Figure 12. Structural diagram of the hole-covering device: 1. Frame. 2. Lifting pull line. 3. Limiting shaft. 4. Hinge shaft. 5. Soil-turning pull rod. 6. Reflector. 7. Soil-turning shell. 8. Soil-sliding trough. 9. Control rod. 10. Traction rod.](image)

As shown in Figure 13, during the operation, the soil thrown out by the straddling ridge-forming and soil-conveying device flows into the soil-turning shell from the soil-sliding trough. The control rod cooperates with the traction rod to pull the lifting pull line, which in turn pulls the soil-turning shell to rotate around the hinge shaft. To prevent the soil-turning shell from over-rotating due to inertia, the limiting shaft controls its rotation angle. When the soil-turning shell is flat, it receives the soil, and when it is turned up, the soil falls from the soil-sliding trough to the film edge for film edge covering.

The control lever is coaxially mounted with the upper crank of the film-piercing and hole-punching mechanism, so the soil-turning shell is turned up once for every plant spacing as the machine moves forward. The static friction angle between soil and steel is 18.26 degrees. To ensure the flowability of soil, the lifting angle of the soil-turning shell is designed to be 60 degrees, which is much greater than the static friction angle between soil and steel. One end of the lifting pull line is connected to the soil-turning pull rod, and the other end is connected to the traction rod. Since the covering of holes with soil is completed during the forward movement of the machine, the lifting speed of the soil-turning shell affects the covering of soil. If the lifting speed is too slow, the covered soil will flow into strips. With the angular velocity of the control lever rotation is determined (i.e., the same as the speed of the upper crank), ignoring the effect of the lifting wire offset, the smaller the rotation angle of the soil-turning rod, the faster the lifting speed of the soil-turning...
shell. The distance between the connection of the flipping cable to the soil-turning rod and the hinge hole of the soil-turning rod is 30 mm; the distance between the connection of the flipping cable to the traction rod and the hinge hole of the traction rod is 60 mm. The flipping angle of the soil-turning shell is 60°, so the rotation angle of the traction rod is \( \alpha = 30^\circ \), and the flipping time of the soil-turning shell is:

\[
t = \frac{\alpha}{\omega}
\]

where \( \omega \) is the angular velocity of the crankshaft (rad/s).

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**Figure 13.** Structural diagram of the hole-covering device.

### 3.4. Transmission System and Seed-Casting Device

The transmission system of a potato planter with whole plastic–film mulching and covering soil on seeding band is shown in Figure 14. The tractor power output shaft transmits power to reducer A through the universal joint drive shaft. After the output shafts on both sides of reducer A reduce the speed by 1.5 times, the power is transmitted to the straddling ridge-forming and soil-conveying device. The speed of the rear output shaft remains the same, and the power is transmitted to reducer B through the universal joint drive shaft. After being further reduced by 10 times by the reducer B, the power is then transmitted to the film-piercing and hole-punching mechanism, the seeding system, the opening and closing system of hole-forming machine, and the soil-covering device control system.

To meet the design requirements for the rotational speed of the film-piercing and hole-punching mechanism, the rotational speed of the mechanism needs to reach 9 rad/s, which means the rotational speed of the upper and lower cranks is approximately \( n_1 = n_3 = 1.4 \) rot/s. If the low-speed gear of the Dongfanghong tractor’s power output shaft is \( n = 9 \) rot/s, then:

\[
\begin{align*}
\frac{z_1}{z_2} &= \frac{n_2}{n_1} \\
z_1 &= z_3 \\
n_2 &= \frac{1}{10}n
\end{align*}
\]
In the above formula, $z_1$ is the number of teeth on the upper crankshaft sprocket equal to 18; $z_2$ is the number of teeth on the output shaft sprocket of the reducer B equal to 28; $z_3$ is the number of teeth on the crankshaft sprocket equal to 18, and $n_2$ is the output shaft speed of the reducer B in rot/s.

**Figure 14.** Schematic of the transmission system.

As shown in Figure 15, the seed-casting device is composed of a base, a seeding reducer, a fixed disk, and a seeding turnplate. During operation, workers manually place the potato seed into the seed cups on the seeding disk. As the seeding turnplate rotates, when the seed cup reaches the seeding hole of the fixed disk, the seed potato falls out, completing the seeding process.

**Figure 15.** Seed-casting device: 1. Seeding turnplate. 2. Fixed disk. 3. Seeding reducer. 4. Base. 5. Seed cup.
The seed-casting turnplate is designed with 8 seed cups evenly distributed on the turnplate. The film-piercing and hole-punching mechanism completes one cycle of work when the upper crankshaft sprocket rotates 1 circle and the seed-casting turnplate rotates $\frac{1}{8}$ circle. Therefore, the speed ratio between the seed-casting turnplate and the upper crankshaft is 1:8, the speed ratio of the seeding reducer is 1:10, then:

$$\frac{z_4}{z_5} = 10i \quad (7)$$

In the formula, $z_4$ is the number of teeth on the output sprocket of the upper crankshaft, which is taken as 20; $z_5$ represents the number of teeth on the input shaft sprocket of the seed-casting reducer, which is 16.

3.5. Simulation and Analysis of Hole-Covering Process

The ridge-forming and soil-covering mechanism operates through the coordinated work of the straddling ridge-forming and soil-conveying device, which tilts to transport soil, and the hole-covering device, whose soil-turning shell receives the soil and carries out the turning and covering process. There is an interactive force between the soil particles and the machinery. The movement and force states of each soil particle vary, making it difficult to analyze and process through theoretical calculations. Therefore, discrete element simulation is used to explore the interactions between soil particles and the device, simulate the actual working conditions of the soil device and investigate the interaction mechanism between the straddling ridge-forming and soil-conveying device, the hole-covering device, and the soil, and verify the reliability of THE different parts of the device.

3.5.1. Model Establishment and Parameter Setting

According to the research results of previous studies [30,31], the radii of soil particles mainly range from 0.25 mm to 5 mm. The particle size has a significant impact on the time step, when the particle diameter is smaller, the time step is shorter, and the simulation speed is slower. In order to accelerate the simulation process, spheres with a radius of 3 mm are selected as soil particles, and the particles are generated randomly.

During simulation, the soil–soil device, soil–mulch device, and soil–hole-covering device interactions all use the Hertz–Mindlin (no-slip) contact model [32], with simulation parameters as shown in Table 1. The movement of a single scraper includes linear motion along the direction of the scraper, rotational motion around the driving wheel, rotational motion around the driven wheel, the frame is set to be fixed, the mulch is set to move linearly in the opposite direction of the actual machine movement, the soil-turning shell is set to rotate periodically around the hinge axis, and a time difference is set to stagger the motion of the soil-turning shells on both sides.

Table 1. Simulation parameters of discrete element [33].

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil</td>
<td>Poisson ratio</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>density/(kg/m$^3$)</td>
<td>1364</td>
</tr>
<tr>
<td></td>
<td>shear modulus/Mpa</td>
<td>1</td>
</tr>
<tr>
<td>mulch</td>
<td>Poisson ratio</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>density/(kg/m$^3$)</td>
<td>1000</td>
</tr>
<tr>
<td></td>
<td>shear modulus/Mpa</td>
<td>6.1</td>
</tr>
<tr>
<td>hole covering device</td>
<td>Poisson ratio</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>density/(kg/m$^3$)</td>
<td>7850</td>
</tr>
<tr>
<td></td>
<td>shear modulus/Mpa</td>
<td>3500</td>
</tr>
<tr>
<td>soil–soil</td>
<td>coefficient of restitution</td>
<td>0.21</td>
</tr>
<tr>
<td></td>
<td>static friction coefficient</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>rolling friction coefficient</td>
<td>0.27</td>
</tr>
</tbody>
</table>
Table 1. Cont.

<table>
<thead>
<tr>
<th>Material</th>
<th>Parameter</th>
<th>Numerical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil–mulch</td>
<td>coefficient of restitution</td>
<td>0.30</td>
</tr>
<tr>
<td></td>
<td>static friction coefficient</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>rolling friction coefficient</td>
<td>0.34</td>
</tr>
<tr>
<td>soil–hole-covering device</td>
<td>coefficient of restitution</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td>static friction coefficient</td>
<td>0.31</td>
</tr>
<tr>
<td></td>
<td>rolling friction coefficient</td>
<td>0.13</td>
</tr>
</tbody>
</table>

3.5.2. Analysis of Simulation Result

Set the particle factory to be double-sided, with a single size of 100 × 180 mm, a generation rate of $1 \times 10^4$ per second, a simulation step length of $7.39 \times 10^{-5}$ s, a fixed simulation time step of 20% of the Rayleigh time step, a grid size of 3R, and a total simulation time of 8 s. By adjusting various parameters, the optimal effect is achieved when the machine advances at a speed of 0.49 m/s, the spacing between the scrapers is 60 mm, the driving wheel’s rotation speed is 6 rot/s, and the time interval for the single-sided soil shell to turn up is 0.5 s, as shown in Figure 16.

By using the EDEM post-processing options for analysis and processing, as shown in Figure 17, it is easy to see that the plant spacing is 350 mm and the row spacing is 400 mm, indicating that the structural and operating parameters of the device are reasonable. There are more soil particles scattered around the edges of the film, and the covering soil is not concentrated enough. There is still room for improvement in structural optimization, but it has a relatively small impact on the overall soil-covering effect of the machine and can meet the needs of soil-covering operations.

To clarify the uniformity of soil coverage and the quality attributes of the soil piles, the GridBinGroup function in post-processing is used to establish a grid on both sides, as shown in the figure, and to count the quality attributes in each grid, as shown in Table 2. From Table 2 and Figure 18, it can be seen that the quality of the soil piles on the same side does not differ much, but there is a slight difference in the quality of the soil piles on the left and right sides. Therefore, the next step should be to optimize the consistency of soil collection and topsoil coverage on both sides in order to improve the overall topsoil coverage effect.
Figure 17. Simulation of the hole-covering effect.

Figure 18. Quality segmentation measurement of various soil piles.

Table 2. Statistics of soil pile mass on both sides.

<table>
<thead>
<tr>
<th>Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>soil pile mass on left side/kg</td>
<td>0.29</td>
<td>0.30</td>
<td>0.33</td>
<td>0.33</td>
<td>0.32</td>
<td>0.34</td>
<td>0.32</td>
</tr>
<tr>
<td>soil pile mass on right side/kg</td>
<td>0.32</td>
<td>0.36</td>
<td>0.36</td>
<td>0.37</td>
<td>0.35</td>
<td>0.36</td>
<td>0.38</td>
</tr>
</tbody>
</table>

3.6. Field Test
3.6.1. Experimental Conditions and Methods

On 30 March 2024, a field performance test of the potato seeding machine with hole punching and soil covering on the film was conducted at the potato planting base in Tong’anyi Town, Longxi County, Dingxi City, Gansu Province, as shown in Figure 19. The...
The test soil was loess with a moisture content of 17.35%, a bulk density of 1200 to 1350, and the firmness of the soil was lesser than 250,000 Pa. The length of the test site was 100 m, and the width was 60 m, the field was flat, loose, and with few weeds. The average size of the potato seed pieces used were 56.4 mm × 44.3 mm × 31.8 mm, with an average mass of 39.8 g. The supporting power was a 29.4 kW Dongfenghong-MF404 tractor produced by YTO Co., Ltd. (Luoyang, China), and the forward speed of the unit during the test was 0.49 m/s.

Figure 19. Field performance test.

After the completion of the task, according to the standards of GB/T25417-2010, GB/T6242-2006, NY/T987-2006, and NY/T987-2006 [34–37], the operation performance of the seeding machine was used to measure the test values of the full soil coverage rate of film holes, the qualified rate of hole spacing, the rate of hole misalignment, the degree of damage to the light-receiving surface of the film, and the qualified rate of sowing depth under the film. The test area plot was divided into four blocks by drawing a cross line at the midpoint of the length and width of the plot. Two diagonal blocks were randomly selected as test samples. In the sample blocks, five small areas were delineated along the diagonal line, with small areas located at the intersection of the diagonal line and at a distance of 1/5 of the diagonal length from each corner.

The method for determining the full soil coverage rate of film holes, the qualified rate of hole spacing, and the misalignment rate of holes is as follows: Select a plot with a width of one sowing span and a length of 4.2 m (12 theoretical plant spacings). The measurement points are all the holes in the plot. The full soil coverage rate of film holes, hole spacing, and hole deviation are measured sequentially. The full soil coverage rate of the film holes, the qualified rate of hole spacing, and the misalignment rate of the holes are calculated according to Formulas (8)–(10), and the average values are also calculated.

\[ H_f = \frac{f_h}{f} \times 100\% \]  
\[ H_s = \frac{x_h}{f} \times 100\% \]  
\[ H_c = \frac{c_h}{f} \times 100\% \]  

In the equation, \( H_f \) represents the soil coverage ratio on the hole of mulch; \( f_h \) represents total number of soil coverage holes on the mulch; \( f \) represents number of holes on total measuring mulch; \( H_s \) represents qualified rate of hole spacing; \( x_h \) represents qualified...
number of hole distance; $H_c$ represents misalignment rate of holes and $c_h$ represents number of misalignment holes.

The method for determining the degree of damage to the light-receiving surface of the film is as follows: Select a small area with a width equal to the width of a film and a length of 4 m. Measure the lengths of the edges or seams of each mechanical damage site on the light-transmitting surface in the small area, calculate the degree of damage to the light-receiving surface of the film according to Formula (11), and then the average value is calculated.

$$\varepsilon = \frac{1000l_i}{Lb_0}$$  \hspace{1cm} (11)

In the formula, $\varepsilon$ represents the degree of damage to the light-receiving surface of the film (mm/m²); $l_i$ represents the length of the edges or seams of the mechanical damage area of the $i$th film in the area (mm); $L$ represents length of the selected area (m); $b_0$ represents the average width of the light-receiving surface after flattening in the selected area (mm).

The method for determining the qualified rate of sowing depth under film is as follows: Select a plot with a length of 4.2 m (12 theoretical plant spacings), measure six rows and select two rows on the left, middle, and right sides, respectively, with planting holes as measurement points; a total of 10 points are measured. At the measurement points, cut the soil layer vertically, counting the number of qualified sowing depths on the profile, calculating the qualified rate of sowing depth under film in the plot according to Formula (12), and calculating the average value.

$$H_b = \frac{h_s}{h_z} \times 100\%$$  \hspace{1cm} (12)

In the formula, $H_b$ represents the qualified rate of sowing depth under the film (%), $h_s$ represents the number of qualified points for sub-film sowing depth and $h_z$ represents the total number of measured points.

3.6.2. Test Results and Analysis

Using the aforementioned experimental methods, the experimental plots after the completion of the operation were measured by the zones and statistical calculations were performed. The field test results of the potato seeding machine with hole punching and soil covering on the film are shown in Table 3, and part of the measurement and statistical process is shown in Figure 20.

Table 3. Results of field test.

<table>
<thead>
<tr>
<th>Item</th>
<th>Average Number</th>
<th>Quality Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>the soil coverage ratio on the hole of mulch, %</td>
<td>94.8</td>
<td>≥90.0</td>
</tr>
<tr>
<td>qualified rate of hole spacing, %</td>
<td>87.6</td>
<td>≥80.0</td>
</tr>
<tr>
<td>misalignment rate of boreholes, %</td>
<td>4.3</td>
<td>≤6.0</td>
</tr>
<tr>
<td>the degree of damage to the light-receiving surface of the film, mm/m²</td>
<td>33.4</td>
<td>≤55.0</td>
</tr>
<tr>
<td>the qualified rate of sowing depth under the film, %</td>
<td>95.6</td>
<td>≥85.0</td>
</tr>
</tbody>
</table>

The field test results indicate that the soil coverage ratio on the hole of mulch, the qualified rate of hole spacing, the misalignment rate of holes, the degree of damage to the light-receiving surface of the film, and the qualified rate of sowing depth under the film are 94.8%, 87.6%, 4.3%, 33.4 mm/m², and 95.6%, respectively. The field performance test indicators met the requirements of the national and industry standards. Therefore, the integrated operation of ridge formation for potatoes, hole sowing on the film, and soil covering on the holes can be achieved.
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<tr>
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<td></td>
</tr>
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4. Conclusions

(1) The field test results indicate that the soil coverage ratio on the hole of mulch, the qualified rate of hole spacing, the misalignment rate of holes, the degree of damage to the light-receiving surface of the film, and the qualified rate of sowing depth under the film are 94.8%, 87.6%, 4.3%, 33.4 mm/m², and 95.6%, respectively. The field performance test indicators met the requirements of the national and industry standard, and the actual operation effect conforms to the agronomic requirements for potato planting.

(2) According to the agronomic requirements of potato planting, this study sets the planting row spacing to be 40 cm and plant spacing to be 35 cm. There is a need to coordinate the plant spacing with the forward speed of the machine. The design of a plant spacing control device not affected by the forward speed of the unit is a future research direction. The team has proposed a plant spacing control device based on the principle of stepless speed change to address the existing shortcomings of the machine.

Author Contributions: Methodology, B.L., W.S. and Z.Z.; investigation, B.L., W.S. and Z.Z.; software, B.L. and W.S.; formal analysis, W.S. and Z.Z.; resources, W.S.; writing—original draft, B.L.; writing—review and editing, W.S., Z.Z. and P.A.S.; funding acquisition, W.S. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China grant NSFC (52165028), Gansu Provincial University Industry Support Plan (2022CYZC-42), and the Key Scientific and Technological Program of Gansu Province (22ZD6NA046).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.
Agronomy 2024, 14, 1570

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