

DESIGN AND EXPERIMENT OF A PIT DIGGING AND PLANTING MECHANISM FOR CUP-TYPE HANGING TOBACCO TRANSPLANTER

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Abstract - To address the issues of inconsistent planting quality and low mechanization efficiency associated with manual tobacco transplanting on flat terrain, this study proposes a fully automatic tractor-mounted cup-type hanging transplanter. The developed device comprises a ground-wheel driven power transmission system, a shovel-type pit-digging mechanism, and a hanging-cup seedling placement unit, enabling coordinated pit-digging and transplanting operations under tractor traction. The dynamic interactions between the soil-engaging components and bulk soil particles were investigated using a coupled EDEM-RecurDyn simulation approach. In the simulation experiments, three operational parameters-namely forward speed, shovel installation height, and shovel installation spacing-were selected as independent variables, while the pit-depth qualification rate and transplanting centering accuracy were adopted as performance evaluation criteria. The simulation results identified the optimal parameter combination as a forward speed of 0.40 m/s, an installation height of 55 mm, and an installation spacing of 550 mm. Based on these optimized parameters, a physical prototype was manufactured and subsequently tested in field conditions. The field trial results showed a pit-depth qualification rate of 98.30% and a centering accuracy of 97.70%, thereby validating the structural soundness and parameter rationality of the proposed design. Overall, this research provides a theoretical foundation and practical guidance for the design optimization of tobacco transplanting machinery.

Keywords: Tobacco, Pit digging, Transplanter, EDEM, RecurDyn.

1. Introduction

In China, the annual tobacco cultivation area has consistently exceeded 1 million hectares [1]. The primary cultivation method involves seedling nursery transplantation, wherein tobacco seedlings cultivated in greenhouse environments are transplanted to field conditions during suitable early-spring temperatures. Timely transplantation promotes subsequent developmental stages of tobacco plants, thereby enhancing both quality and yield [2]. The transplantation process requires prior pit formation to provide an optimal growth environment for seedlings. Transplantation efficiency and quality directly influence tobacco product quality, yield, and economic returns [3]. As a core component of tobacco transplanters, the pit-digging mechanism significantly impacts transplantation performance. Well-designed pit-

digging devices are crucial for ensuring seamless transplantation operations [4].

Due to the high susceptibility of tobacco seedlings to wilting, immediate post-transplantation irrigation is vital, requiring integrated watering functions in transplanters. The development of tobacco transplanters has progressed slowly, resulting in limited availability of advanced equipment comparable to that used for vegetables or rice. Consequently, existing machinery fails to fully meet the specific agronomic requirements for flue-cured tobacco cultivation [5-8]. With tobacco companies increasingly promoting large-scale cultivation practices and centralized field management, prerequisites for high-efficiency agricultural machinery are being established. Currently, there are few transplanters for tobacco in domestic and international markets.

The tobacco transplanting process requires significant labor input, and the development and promotion of transplanters are key steps to achieve efficient tobacco cultivation [9-11]. In recent years, various transplanting machines have been widely used in tobacco and vegetable production. However, most existing transplanting machines suffer from problems such as poor adaptability, unstable planting depth, and low efficiency of parameter matching. Compared with traditional transplanting machines, this study proposes the integration and optimization of a pit-drilling and transplanting mechanism, which can simultaneously complete pit forming, transplanting, and water irrigation in one pass. Moreover, the depth and centering accuracy of both pit drilling and transplanting are adjustable, thereby improving transplanting quality.

Despite the widespread application of transplanting machines in tobacco and vegetable production, a critical review of existing pit-digging and transplanting mechanisms reveals several inherent limitations. Most current designs separate pit formation from seedling placement into two independent operations, which often leads to poor temporal and spatial coordination between the two actions. This disconnection frequently results in misalignment between the planting pit and the seedling, causing tilted or shallow planting that compromises seedling survival and subsequent growth. Furthermore, existing mechanisms typically offer fixed or very limited adjustability of pit depth and transplanting position, making it difficult to adapt to variations in soil conditions, ridge morphology, and moisture content across different fields. Even when adjustments are possible, they are often performed empirically without systematic parameter matching for tobacco-specific agronomic requirements. Consequently, there remains a notable technical gap: few studies have systematically addressed the integrated design and parameter optimization of a combined pit-digging and transplanting mechanism specifically for tobacco, with coordinated motion trajectories and independently adjustable parameters. This study aims to fill this gap by proposing a novel hanging-cup type tobacco pit-digging and transplanting mechanism that integrates pit excavation and seedling placement in a single coordinated unit, with independently adjustable installation parameters and systematic optimization through coupled simulation and field validation.

Tobacco transplanting in plain-growing regions traditionally requires sequential operations: ridging, pit digging, seedling insertion, and irrigation for root establishment. To address the inefficiencies caused by these separate steps, this paper proposes a novel hanging-cup type tobacco pit-digging and transplanting mechanism that integrates pit

excavation and seedling placement in a single coordinated unit. A distinctive feature of this design is the independently adjustable installation height and horizontal distance between the pit-digging shovel and the suspended-cup planter, which enable flexible regulation of pit depth and transplanting centering accuracy to suit varying field conditions. Through coupled EDEM-RecurDyn simulations, the influence of key operational parameters on transplanting quality is systematically investigated. A traction-type prototype was subsequently developed and validated under field conditions. This research provides both a practical design solution and technical guidelines for optimizing tobacco transplanting mechanisms across diverse soil environments.

2. Materials and Methods

2.1. Overall Structure and Working Principle

2.1.1 Agronomic Requirements for Tobacco Transplanting

Tobacco, as a ridge-cultivated crop, requires transplanting operations in prepared ridges after rotary tillage. The ridges should be plump and tile-shaped, with smooth surfaces free of large clods, and trenches should be level while ridges straight. The planting pits must be deep and wide to facilitate deep tobacco seedling planting, while maintaining uniform plant spacing. All transplanting agronomic parameters are listed in Table 1. Additionally, each tobacco seedling should receive at least 0.5L of water during transplanting, followed by immediate drip irrigation after planting [12-14].

Table 1. Agronomic requirements for tobacco transplanting

Type	Parameter range
Ridge height/mm	>250
Ridge spacing/mm	1100-1200
Ridge base width/mm	700-900
Ridge top width/mm	300-400
Pit spacing/mm	450-550
Pit depth/mm	90-120
Pit opening diameter/mm	250-300
Planting depth/mm	10-15
Plant spacing/mm	450-550

2.1.2 Integrated Machine Structure Design

The traction tobacco transplantation machine comprises several main components: floor wheels, planting beds, planting devices, rear seats, soil augers, an automatic seedling delivery system, and a suspension frame. The machine performs pit digging, seedling transplantation, and water injection in a single pass along each tobacco ridge.

The overall structure is illustrated in Figure 1. A three-point suspension frame is mounted at the front of the transplanting machine and connects to the tractor via a three-point linkage system, which provides the driving power. The left and right wheels operate between two adjacent tobacco ridges to guide the machine. The pit-digging and planting devices are mounted on the main beam, while the automatic seedling delivery system is positioned above the planting mechanism. Seedling trays are placed on both sides to enable seedling supplementation as needed.

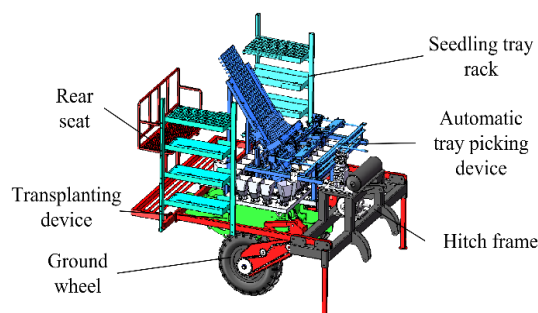


Figure 1: The complete tractor tobacco transplanter

During pit digging and transplanting operations, the tractor propels the transplanter forward. The ground wheel drives the pit digging mechanism to excavate planting pits, followed by the activation of the suspended-cup planter to transplant tobacco seedlings. Upon completion of transplantation, the irrigation mechanism applies water to the seedlings, thereby completing a full transplanting cycle.

2.2 Critical Component Design

2.2.1 Working Principle of the Pit Digging and Transplanting Mechanism

The pit digging and transplanting device is the core component of the traction-type tobacco transplanter [15, 16]. As shown in Figure 2, the suspended-cup pit-digging and transplanting system consists of a ground wheel, a pit-digging mechanism, a suspended-cup planter, and a multi-stage transmission mechanism. The transplanter is towed forward by a tractor. During forward motion, the ground wheel rotates, driving the transmission main shaft via a chain. The main shaft transfers power downward to the pit digging mechanism and the cup-type hanging planting mechanism. The pit-digging mechanism first excavates the planting pit, after which the planting mechanism inserts the tobacco seedling into the newly formed pit, thereby completing one pit-digging and transplanting cycle.

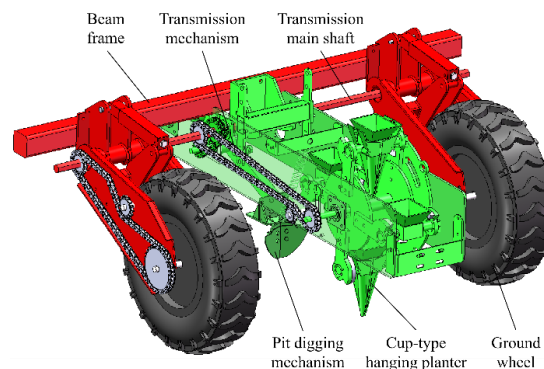


Figure 2: Schematic diagram of pit digging and transplanting structure

2.2.2 Design of the Transmission System

The traction-type transplanter achieves fixed plant spacing for tobacco seedlings by driving the seedling transplanting mechanism via sprockets, chains, and rotating shafts. Figure 3 illustrates the power transmission schematic of the transplanter. As the tractor tows the transplanter forward, the rotation of the left and right ground wheels drives the chain transmission to transfer power to the main transmission shaft. The main shaft then activates the pit digging mechanism through chain transmission, while the planter drive chain powers the cup-type hanging planter. By replacing the sprockets on the ground wheels, the transmission ratio between the ground wheels and the main shaft can be adjusted to modify the plant spacing. The planter transplants two seedlings per revolution. To ensure synchronization between pit-digging and transplanting, the pit-digging mechanism must complete two motion cycles within one revolution of the planter, requiring a transmission ratio of 1:2 between the two mechanisms. In accordance with the mechanical design manual, this design employs sprockets and chains of type 10A. Based on the transmission structure, the plant spacing satisfies the following relationship derived from (1):

$$l = \frac{Z_2 \pi D}{2Z_1} \quad (1)$$

where D is the ground wheel diameter (600 mm), Z_1 is the number of teeth on the driving sprocket of the ground wheel, and Z_2 is the number of teeth on the driven sprocket of the planter. The calculated plant spacing l is 502.65 mm.

This designed transplant spacing meets the agronomic requirements for tobacco transplantation in the plain tobacco-growing regions of Henan.

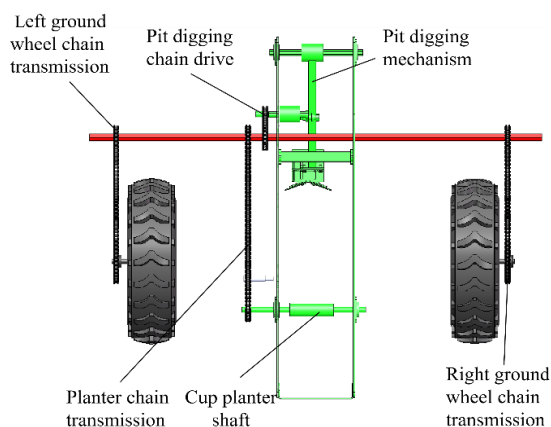


Figure 3: Transmission route map

2.2.3 Design of the Pit Digging Mechanism

The designed pit digging mechanism is shown in Figure 4. As the ground wheel rotates, it drives the main transmission shaft, which then transfers power via a chain drive to rotate the pit digging crank. The crank presses the swing arm downward, causing it to pivot around the central axis and push the digging shovel to its lowest position. When the shovel reaches the lowest point, the crank begins to move upward. Assisted by the spring mechanism, the digging shovel and swing arm return to the highest position, completing one pit digging cycle. To accommodate agronomic requirements across different regions, both the installation depth and fore-aft position of the digging shovel are designed to be adjustable.

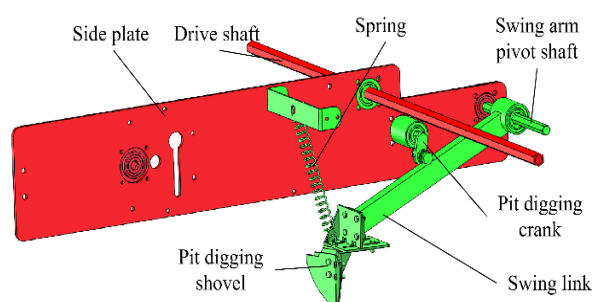


Figure 4: Pit digging mechanism

2.2.4 Design of the Planting Mechanism

The traction-type tobacco transplanter employs a technologically mature duckbill-type suspended-cup transplanting mechanism as its planting unit. Driven by the rotation of the ground wheel, the duckbill mechanism completes two seedling insertions per revolution, thereby accomplishing the planting process under the traction force of the tractor.

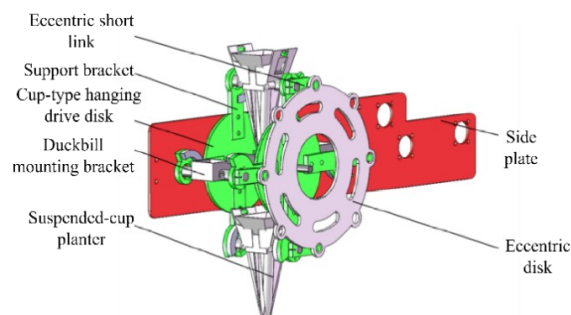


Figure 5: Suspended-cup transplanting mechanism

As shown in Figure 5, the suspended-cup planter is fixed to the duckbill mounting bracket. The eccentric disk is mounted on the side plate, and the cup-type hanging drive disk rotates synchronously with the transplanter shaft. The distance between the rotational centers of the eccentric disk and the drive disk equals the motion range of the eccentric short link, forming a parallelogram mechanism composed of the eccentric disk, duckbill mounting bracket, eccentric short link, and drive disk. According to Grashof's theorem, with the eccentric disk and drive disk acting as two equivalent cranks, the eccentric short link and duckbill mounting bracket will maintain parallelism to the ground during motion, provided that the line connecting the centers of the eccentric disk and drive disk is installed parallel to the ground. Since the suspended-cup planter is vertically mounted on the bracket, this configuration ensures the planter remains perpendicular to the ground throughout operation, achieving consistent vertical soil penetration.

2.3 Simulation Test

2.3.1 Construction of Kinematic Model for Pit Digging and Transplanting Structure

A RecurDyn simulation was conducted to study the pit digging performance under operational conditions of the pit digging and transplanting machine [17-21]. The pit-digging mechanism and transplanting mechanism were modeled in 3D using SolidWorks. To optimize computational efficiency, only the pit-digging and transplanting processes were included in the dynamic simulation, while components such as chain drives, partial frames, and bolts were simplified. After completing the model, an interference check was performed to ensure the rationality of the 3D structure. The model was then exported in (x_t) format and imported into RecurDyn. The digging shovel and suspended-cup planter were assigned steel material properties. In RecurDyn, simulation parameters such as mass properties, constraints, and loads were applied to the mechanisms. The pit digging and transplanting mechanisms are shown in the accompanying figures.

In the preprocessing module, constraints were applied to each component based on their kinematic behavior (Table 2 lists the constraint relationships).

Table 2. Kinematic constraints of components in the pit digging and transplanting mechanism

Connecting piece	Kinematic pair
Frame and ground	Translate
Swing arm and frame	Revolute
Cover and rack	Revolute
Pit-digging shovel and swing arm	Revolute
Ground wheel and rocker arm	Revolute
Cup power disc and rack	Revolute
Cup Power disc and suspended-cup planter A	Revolute
Hanging cup dynamic disc and suspended-cup planter B	Revolute
Eccentric disk and frame	Revolute
Eccentric discs and suspended-cup planter A	Revolute
Eccentric discs and suspended-cup planter B	Revolute

During operation, the tobacco transplanter is towed forward by a tractor, with power transmitted from the ground wheel to the pit digging mechanism and transplanting mechanism via chain drives. The simulation software primarily controls rotation through angular velocity. To ensure consistency between simulation and real-world conditions, the working speed (linear velocity) is converted to rotational angular velocity using the formula $\omega = 2\pi n$, where n is the rotational speed in revolutions per second (r/s). A spring is added between the mounting holes of the frame spring seat and the digging shovel spring bracket based on their geometric relationship. A translational driving function at 0.40 m/s along the X-axis is applied to the translational joint between the frame and the ground. Rotational driving functions of $288^\circ/\text{s}$ and $144^\circ/\text{s}$ are applied to the revolute joints of the crank-frame and the planter-fixing-disk-frame connections, respectively. The simulation duration is set to 5 s with 250 steps.

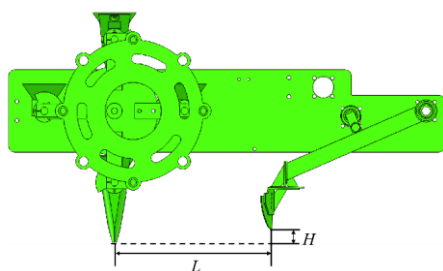


Figure 6: Pit digging and transplanting mechanism

Note: L is the horizontal distance between the lowest point of the pit-digging shovel and the lowest point of the suspended-cup planter; H is the pit-digging shovel installation height.

According to the three-dimensional modeling design parameters, when the pit-digging shovel moves to its lowest position, the shovel face is oriented vertically toward the ground, and at this moment the suspended-cup planter also reaches its lowest point. Taking the lowest point of the suspended-cup as the reference plane, the height of the pit-digging shovel relative to this plane is defined as the pit-digging shovel installation height (i.e., H in Figure 6).

The pit-digging depth can be adjusted by modifying the installation height. To ensure optimal transplanting performance, the lowest point of the suspended-cup planter should align with the lowest point of the pit when it reaches its lowest position. By utilizing the horizontal fixing bolts and sliding slots of the pit-digging shovel, the horizontal distance between the lowest point of the pit-digging shovel and the lowest point of the suspended-cup planter (i.e., L in Figure 6) can be continuously adjusted within the range of 460–580 mm. For brevity, the horizontal distance between the pit-digging shovel and the suspended-cup planter is denoted as L , and the pit-digging shovel installation height is denoted as H . For example, L460H35 denotes a horizontal distance of 460 mm and a height of 35 mm, while L540H55 denotes a horizontal distance of 540 mm and a height of 55 mm. As shown in Figure 7 with configurations L460H55, L500H55, and L540H55, the red solid line represents the trajectory of the pit-digging shovel's lowest point; the green dotted line represents the trajectory of suspended-cup planter A; and the blue dashed line represents the trajectory of suspended-cup planter B. It can be observed that the suspended-cup planter trajectory follows a curtate cycloid pattern, forming a water-drop-shaped trajectory at the lowest point of soil entry, which extends the transplanting duration and improves seedling verticality. Based on the simulation trajectory analysis, with the forward direction as positive, when the horizontal distance is 460 mm, the suspended-cup planter transplants at the forward position of the pit. When the horizontal distance is 500 mm, the lowest point of the suspended-cup planter coincides with the lowest point of the pit. When the horizontal distance is 540 mm, the suspended-cup planter transplants at the rear position of the pit. Comparative observation of configurations L500H35 and L500H55 in Figure 7 demonstrates that adjusting the pit-digging shovel depth setting can regulate pit-digging depth without affecting transplanting depth. Transplanting depth can be adjusted through the ground-wheel mechanism of the overall machine structure shown in Figure 7.

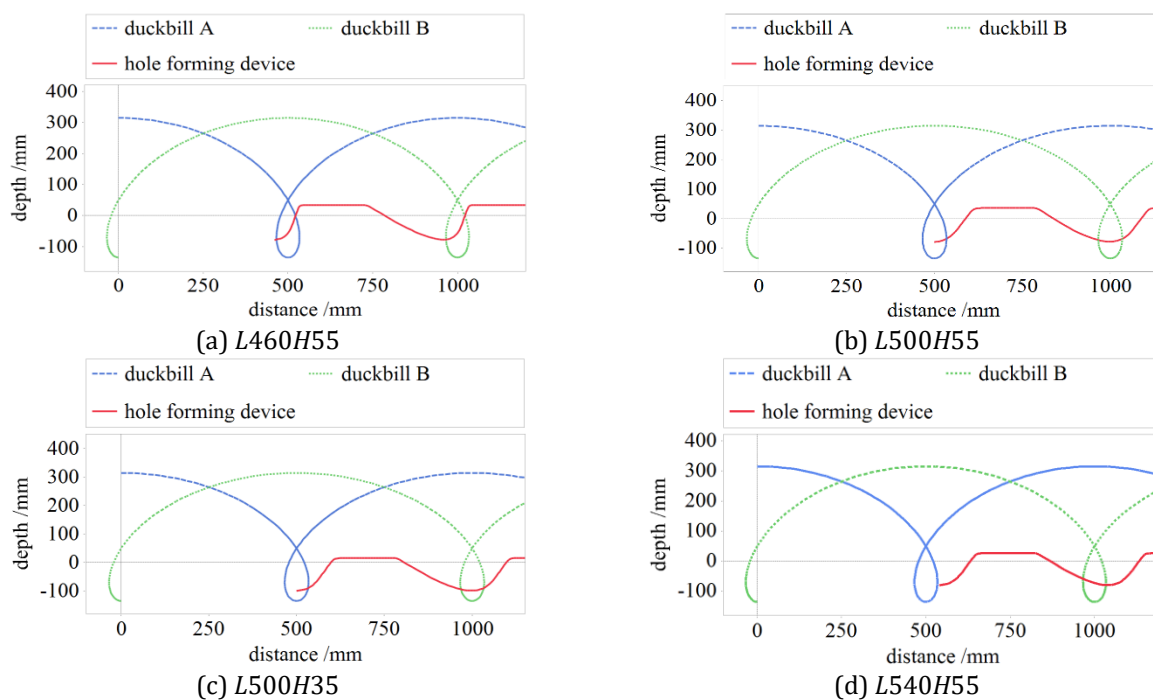


Figure 7: Trajectory of pit forming device and suspended-cup planter

The transplanting machine's performance significantly impacts the quality of tobacco transplantation. During mechanical transplanting, seedling damage—including root rupture, leaf bruising, and tissue injury—directly affects seedling survival rates post-transplantation. Minimizing seedling damage during transplanting is critical to ensuring high survival rates [22, 23]. Figure 8 illustrates the velocity profiles of the suspended-cup planter during transplanting. The blue dotted line represents the horizontal velocity of the planting device, while the red solid line represents the horizontal velocity of the suspended-cup planter. These velocity profiles exhibit significant fluctuations resulting from the water-drop-shaped motion trajectory described previously. During the soil insertion phase, the suspended-cup planter descends into the ridge, deposits the seedling into the planting pit, and retracts from the ridge to complete the transplanting cycle. Because the machine continues moving forward, seedlings experience inertia forces during ejection from the planter, which can cause tilting and result in seedling damage. To minimize this damage, the planter velocity should approach zero during seedling release—a principle termed "zero-speed transplantation."

Analysis of Figure 8 reveals that during the soil insertion phase, when the velocity profile exhibits minimal fluctuation, the planter velocity ranges between -200 and $+200$ mm/s. During the remaining operational phases, the planter can reach velocities up to $1,000$ mm/s. Because the motion trajectory is water-drop-shaped, the planter's motion is partially offset by the forward motion of

the machine during transplanting, thereby achieving optimal seedling placement and minimizing damage.

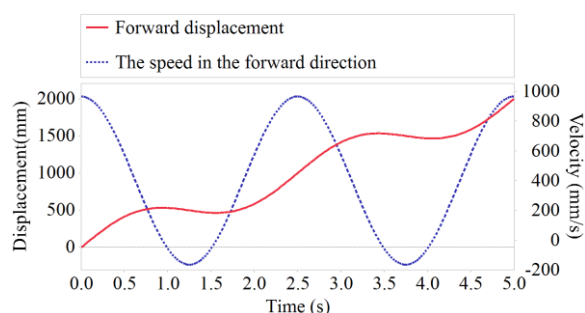


Figure 8: The relationship between the forward distance, horizontal velocity, and time of suspended-cup planter

2.3.2 Establishment and Parameter Calibration of Soil Discrete Element Model

The angle of repose can reflect the flowability and frictional characteristics of soil. In this experiment, the parameters of the soil discrete element model were verified by combining bench tests and simulation. In the actual test, the angle of repose of the soil was measured by the cylinder lifting method. The cylinder dimensions were 400 mm (diameter) $\times$ 1600 mm (height). During the test, soil particles were first packed into the entire cylinder, and then the cylinder was slowly lifted at a speed of 0.1 m/s. Under the action of its own gravity, the soil would naturally fall from the bottom and gradually accumulate. When the soil was completely stable, the angle between the slope and the horizontal plane was the angle of repose.

The simulation conditions replicated those of the physical test, with identical cylinder dimensions.

The cylinder was lifted at 0.1 m/s. The simulation test process is shown in the following Figure 9.

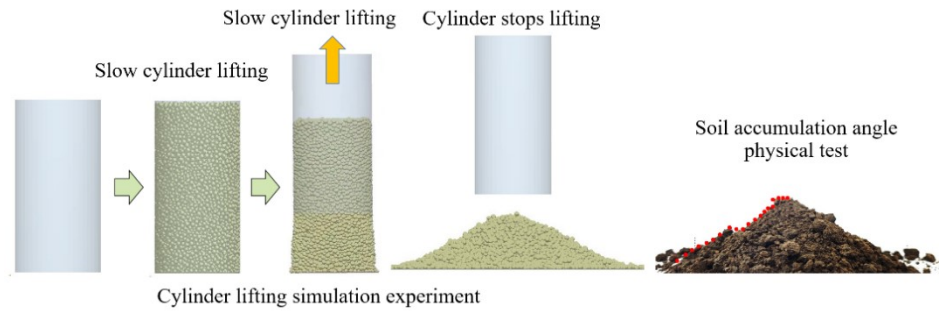
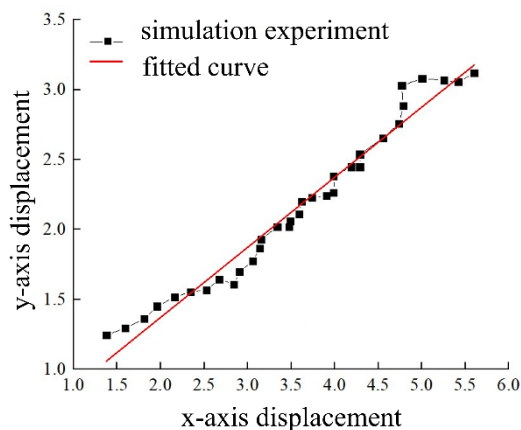


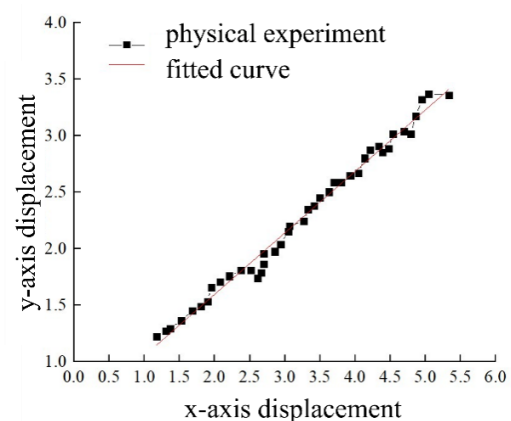
Figure 9: Simulation of soil accumulation angle and comparison with physical experiments

After the experiment was completed, in order to reduce the error of manual measurement, a high-definition camera was used to directly observe the soil accumulation angle and collect image information. The Origin image digitization processing technology was employed to extract the data points of the soil slope. The coordinate values in the horizontal and vertical directions were set and linear fitting was performed. The slope of the fitted straight line was converted into the soil accumulation angle (Figure 10). The analysis showed that the slope of the fitting curve in the

simulation experiment was 0.50, and the average value of the soil accumulation angle was 26.6° ; in the actual experiment, the average value of the straight line slope was 0.54, and the average value of the accumulation angle was 28.3° . The error between the soil accumulation angle of the simulation experiment and the actual experiment was 6.0%, indicating that the simulation results were basically consistent with the experimental results. Therefore, the soil particle discrete element model can be used for the simulation experiment.



(a) Simulation test fitting curve



(b) physical test fitting curve

Figure 10: Fitting curve of the simulation and the actual pile-up angle test

2.3.3 Establishment of Discrete Element Model for Tobacco Ridges

Soil is a typical discrete medium. Based on the actual dimensions of the tobacco ridge, a discrete element model of the ridge was constructed using EDEM software, with a ridge length of 2000 mm and a soil particle radius of 2 mm. Using the kinematic model for the pit-digging and transplanting structure developed in RecurDyn software as described above, the pit-digging process was investigated [24-29], as illustrated in Figure 11.

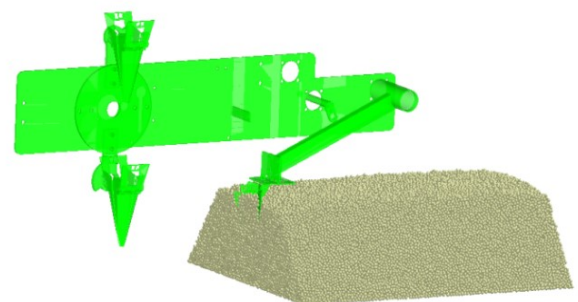


Figure 11: Coupling model between the pit-digging and transplanting device and the tobacco ridge

During the transplanting process, the interaction between the pit digging shovel and the ridged soil model involves continuous mechanical forces. The intrinsic and contact parameters of the soil directly influence the experimental outcomes. Based on Hertzian theory, this study introduces the JKR model to characterize the agglomeration effect among soil particles caused by water molecule interactions. A Hertz-Mindlin (no-slip) contact model is applied between the soil and the pit-digging shovel, effectively simulating the soil fluidity observed during the disturbance caused by soil-engaging components such as the cavity-forming shovel. Considering the specific properties of tobacco field soil and referencing relevant literature [30], the JKR surface energy between soil particles was set to 3.50. The intrinsic parameters of the ridged soil and shovel components were determined, and their contact parameters were established. The specific parameters are presented in Table 3.

Table 3. Parameter table of discrete element simulation

Project	Value
Poisson's ratio of soil, μ_1	0.38
Soil particle density, ρ_1 / (kg/m ³)	1569
Shear modulus of soil particles, G_1 / (Pa)	1.01×10^6
Poisson's ratio of pitforming device(steel), μ_2	0.3
pit forming device density, ρ_2 / (kg/m ³)	7800
Shear modulus of hole forming device, G_2 / (Pa)	8×10^{10}
Recovery coefficient of collision between soil particle	0.45
Coefficient of static friction between soil particles	0.54
Coefficient of dynamic friction between soil particles	0.05
Recovery coefficient of collision between soil particle and pit forming device	0.5
Coefficient of static friction between soil particles and pit forming device	0.5
Coefficient of dynamic friction between soil particles and pit forming device	0.1

A tobacco model was established using EDEM, with soil particles configured to fall at -2 m/s in the Y direction over a simulation duration of 2 s. To facilitate clear observation of the soil state, the transparency of the tobacco model was adjusted.

Regarding the simulation parameters, the time step in EDEM was set to 1.5×10^{-6} s, the total simulation time was set to 10 s, and data was saved every 0.02 s.

2.3.4 Joint Simulation Model Analysis

Traditional research methods are unable to adequately characterize the influence of the structural and operational parameters of the pit-digging and transplanting device on soil flow behavior. The combined simulation of EDEM and RecurDyn can effectively simulate the interaction between the tobacco ridge and the pit digging and transplanting device. After opening the two-way coupling interface of EDEM and RecurDyn, the simulation time is set to 5 s. By selecting Display Animation on the RecurDyn simulation page, the entire movement process of pit-digging can be observed in RecurDyn. The coupling model of the pit-digging and transplanting device and the tobacco ridge is shown in Figure 12.

Based on the designed pit-digging structure, three horizontal installation distances were examined at a constant height and operating speed for simulation analysis. As shown in Figure 13, the soil depth was divided by color for the advantages of real-time capture of the dynamic mechanical changes of soil particles and visual display of the results, etc.

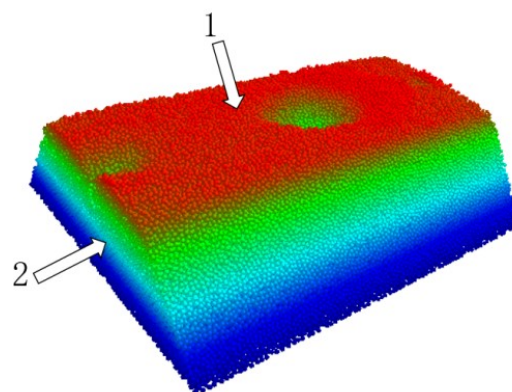


Figure 12: Coupling simulation result diagram

To observe the dimensions of the holes more intuitively, the CLIPPING function of EDEM was adopted. Two slices were made along the planes indicated by arrows 1 and 2 in Figure 12 to observe the morphology of the holes. The size measurement function in the post-processing of EDEM was utilized to measure the parameters of the holes.

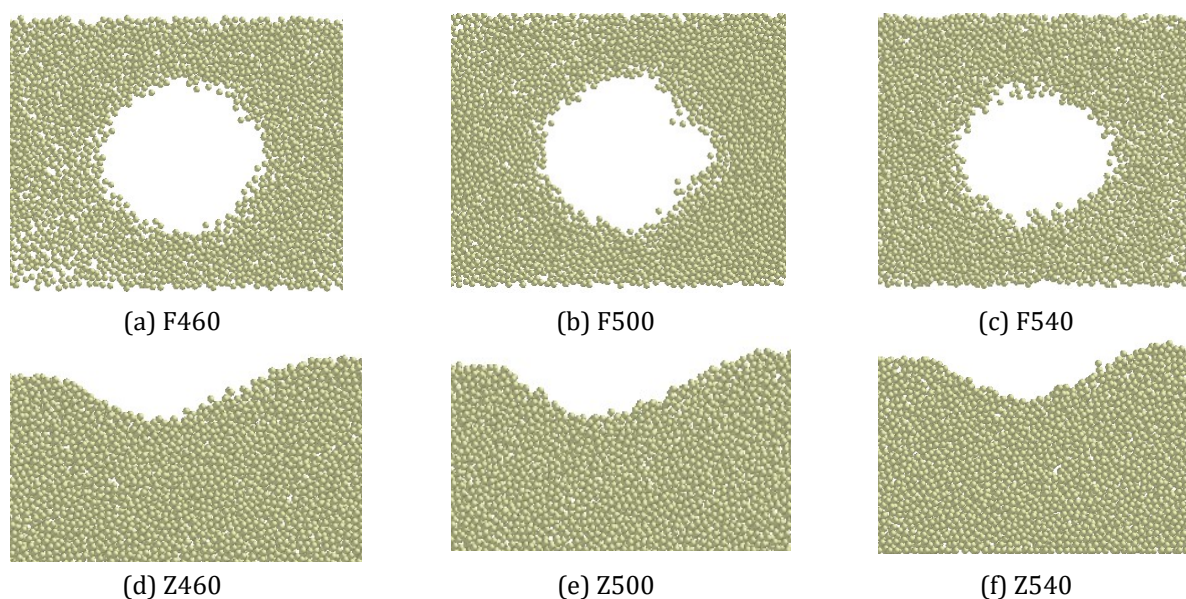
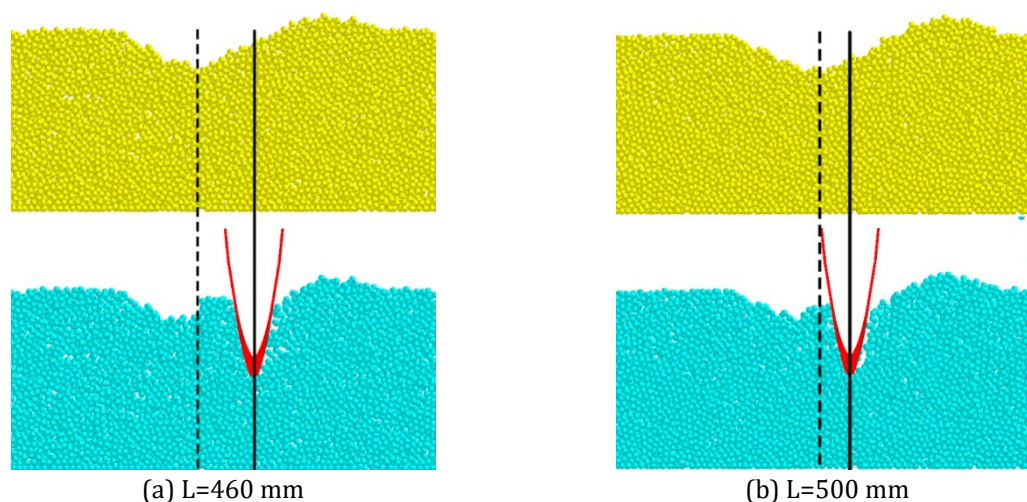


Figure 13: Coupling simulation of pit formation

The pit-digging configuration is illustrated in Figure 13. The top-view images (F460, F500, F540) demonstrate the effects of varying horizontal installation distances while maintaining a fixed pit-digging shovel mounting height of 55 mm and a forward speed of 0.4 m/s. The side-view images (Z460, Z500, Z540) present the pit-digging profiles under identical parameters. Observations from the top view reveal that pit shape varies slightly with different installation positions; however, the pit opening generally maintains a circular shape. Observations from the side view indicate that because the pit-digging shovel excavates forward, soil on the right side (direction of motion) is elevated relative to the left side. Upon completion of the pitting operation, the loosened soil from prior rotary tillage and ridging exhibits subsidence due to its low cohesion. Subsequent analysis examined the pit trajectory in relation to the planting trajectory. When the horizontal installation distance is 500 mm, the lowest point of the pit aligns with the lowest

point of the suspended-cup planter. As soil subsides following pit formation, the actual pit center shifts backward, causing the suspended-cup planter to be positioned forward of the pit center.

Figure 14 illustrates this relationship, where the yellow region represents the pit formed by the pit-digging shovel, the red represents the suspended-cup planter, and the light blue region represents the soil state when the suspended-cup planter reaches its lowest point. Analysis of Figure 14 reveals the following planting positions as a function of horizontal installation distance: At $L = 460$ mm, the suspended-cup planter is positioned ahead of the pit. At $L = 500$ mm, the suspended-cup planter is aligned with the pit center. At $L = 540$ mm, the suspended-cup planter is positioned slightly behind the pit center. At $L = 580$ mm, the suspended-cup planter is positioned behind the pit. These varying positions enable optimization of seedling placement depth and survival rate based on soil conditions.



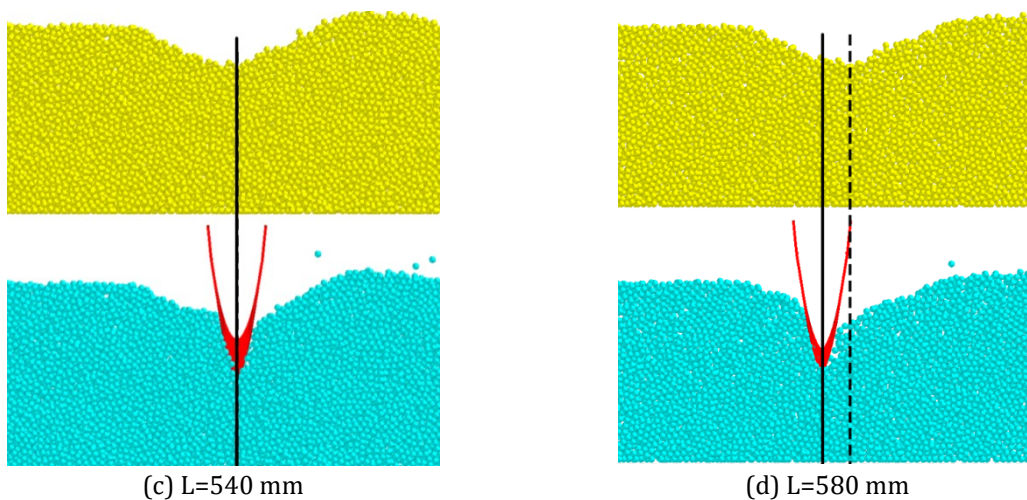


Figure 14: Relationship between pit digging and transplanting

2.3.5 Single-factor Simulation Experiment

(1) Pit-digging depth

Based on preliminary experiments, the depth of pit formation is primarily influenced by the installation height of the pit digging shovel. With the operational speed fixed at 0.4 m/s and the installation distance of the pit digging set at 540 mm as constant factors, a single-factor experiment was conducted to investigate the effects of installation heights of 15, 35, 55, 75, and 95 mm on the pit formation depth. Each experimental group was repeated three times, and the average values were calculated. The collected data were analyzed, revealing the following relationship between pit digging depth and installation height.

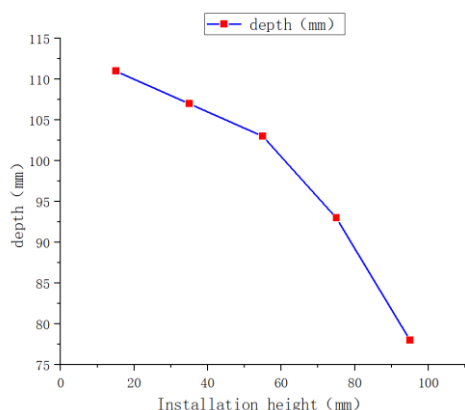


Figure 15: Relationship between pit digging depth and installation height of pit digging shovel

Figure 15 demonstrates that as the pit-digging shovel mounting height increases, the pit depth decreases. Specifically, higher mounting heights result in shallower pits with lower soil displacement. Conversely, when the pit-digging shovel height is relatively low, the lowest point of the shovel penetrates deeper into the soil, resulting in deeper pits with greater soil displacement. The relationship is inverse: as the mounting height increases, the pit

depth gradually decreases, and the amount of soil returned to the pit decreases correspondingly. According to agronomic requirements, pit-digging depth must be maintained within the range of 90–120 mm. To meet agronomic requirements across diverse soil conditions and considering practical shovel operation, two mounting height settings—35 mm and 55 mm—are provided to adjust pit depth.

(2) Transplanting centering

Seedling placement neutrality is defined as the positional relationship between the suspended-cup planter's lowest point and the pit center. When the suspended-cup planter's lowest point aligns with the pit center, neutrality is achieved; negative values indicate the planter is positioned ahead of the pit center. Preliminary testing indicated that neutrality is primarily influenced by the horizontal distance between the pit-digging shovel and the suspended-cup planter. To systematically evaluate this relationship, tests were conducted at a fixed forward speed of 0.4 m/s and a fixed pit-digging shovel mounting height of 55 mm. The installation position of the pit digging shovel was selected as 500, 520, 540, 560 and 580 mm, and the single-factor test was designed. Each group was repeated three times, and the averaged data are presented in Figure 16, showing the relationship between transplanting centering and installation distance.

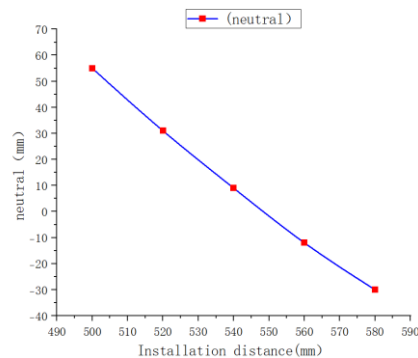


Figure 16: Relationship between transplanting centering and horizontal installation distance

Figure 16 demonstrates that as the horizontal installation distance between the pit-digging shovel and suspended-cup planter increases, the neutrality value transitions from positive to negative. Neutrality values closer to zero indicate more precise alignment between the suspended-cup planter's lowest point and the pit center, resulting in improved seedling placement accuracy. According to agronomic requirements, acceptable transplanting error tolerance for pit-digging operations is ± 20 mm. The optimal horizontal installation distance range of 540–560 mm satisfies this requirement.

2.3.6 Central Composite Design Experiment

Based on the results of the single-factor simulation tests in Section 2.3.5, a central composite design (CCD) with two factors and five levels was adopted to establish the experimental plan. The installation height H (35–55 mm) and horizontal installation distance L (540–560 mm) were selected as the independent factors (variables).

The qualification rates of pit-digging depth (Y_1) and transplanting centering (Y_2) were taken as the response variables.

The qualification rate of pit-digging depth Y_1 and the qualification rate of transplanting centering Y_2 were taken as the response indicators. The level encoding of the test factors is shown in Table 4, and the test results are presented in Table 5.

Table 4. Factor level coding table for experiments

Code	The pit-digging shovel installation height H /mm	The pit-digging shovel and the suspended-cup planter L /mm
-1.414	35	540
-1	37.93	542.93
0	45	550
1	52.07	557.07
1.414	55	560

Table 5. Experiment protocol and results

No.	The pit-digging shovel installation height H /mm	The pit-digging shovel and the suspended-cup planter L /mm	The qualification rate of pit-digging depth /%	The qualification rate of transplanting centering /%
1	-1	-1	95	87
2	1	-1	85	95
3	-1	1	93	91
4	1	1	97	97
5	-1.414	0	98	96
6	1.414	0	94	97
7	0	-1.414	88	87
8	1	1.414	95	95
9	0	0	97	94
10	0	0	95	97
11	0	0	95	97
12	0	0	95	98
13	0	0	97	98

The variance analysis of the test results was conducted using the Design-Expert 13.0 software, and the results are shown in Tables 6 and 7. The regression model for the pit-digging depth

qualification rate (Y_1) is highly significant ($P < 0.01$), as is the regression model for the transplanting centering qualification rate (Y_2) ($P < 0.01$).

Table 6. Analysis of variance of Y_1

Variance Source	Sum of squares	Degree of freedom	Mean square	F	P
Model	157.75	5	31.55	27.81	0.0002 ^{***}
x_1	16.99	1	16.99	14.97	0.0061 ^{***}
x_2	49.50	1	49.50	43.63	0.0003 ^{***}
x_1x_2	49.00	1	49.00	43.19	0.0003 ^{***}
x_1^2	0.3141	1	0.3141	0.2768	0.6150
x_2^2	42.18	1	42.18	37.19	0.0005 ^{***}
Residual	7.94	7	1.13		
Lack of fit term	3.14	3	1.05	0.8725	0.5257
Error	4.80	4	1.20		
Total sum	165.69	12			

Note: *** indicates that the impact is extremely significant, $P < 0.01$; * indicates that the impact is significant, $P < 0.05$.

Table 7. Variance analysis of Y_2

Variance Source	Sum of squares	Degree of freedom	Mean square	F	P
Modle	139.98	5	28.00	5.26	0.0253 [*]
x_1	29.70	1	29.70	5.58	0.0502
x_2	37.47	1	37.47	7.04	0.0328 [*]
x_1x_2	1.00	1	1.00	0.1879	0.6777
x_1^2	1.49	1	1.49	0.2796	0.6133
x_2^2	71.79	1	71.79	13.49	0.0079 ^{**}
Residual	37.25	7	5.32		
Lack of fit term	26.45	3	8.82	3.27	0.1414
Error	10.80	4	2.70		
Total sum	177.23	12			

Note: **indicates that the impact is extremely significant, $P < 0.01$; * indicates that the impact is significant, $P < 0.05$.

With the optimization objectives of maximizing the qualification rate of pit-digging depth (Y_1) and the qualification rate of transplanting centering (Y_2), and considering the actual field operation conditions of the machine, the optimal parameter combination was determined as follows: prior to transplanting operations, the pit-digging shovel was adjusted to an appropriate position, specifically with the pit-digging shovel installation height set at 55 mm and the distance between the pit-digging shovel and the suspended-cup planter set at 550 mm. Under these conditions, $Y_1 = 94.13\%$ and $Y_2 = 98.00\%$. Further field experiments are required to validate the simulation results.

2.4 Field Testing

2.4.1 Test Conditions

Based on the optimal structural parameters obtained from simulation experiments, a traction-type tobacco transplanter was developed. Field trials were subsequently conducted in May 2024 at tobacco cultivation fields located in Jian'an District, Xuchang City, Henan Province. The experimental field was flat with a light brown color. On the day of transplanting, the weather was cloudy turning overcast, with a south wind of Beaufort force 1–2, temperature ranging from 11 to 23 °C, and soil moisture content of 15%–18%. The field had completed ridging operations according to the agronomic ridge standards previously specified. A Dongfanhong MF804-6 (G4) wheel tractor with a rated power output of 58.5 kW was used as the primary towing vehicle. The tobacco seedlings used were Zhongyan 100 cultivar with an average length of 180 mm, including the substrate and fully formed leaves, meeting established agronomic specifications. Test equipment and instruments included: the traction tobacco transplanter, measuring tapes, straightedges, calipers, and stopwatches. Field trial operations are illustrated in Figure 17.



Figure 17: Field test

2.4.2 Test Method

Field trials were conducted in accordance with the "Operational Performance and Test Methods of Tobacco Seedling Transplanters" [31]. Performance testing and field trials were carried out, with the qualification rate of pit-digging depth and the qualification rate of transplanting centering as the test evaluation indices. The optimal installation height for field trials is determined based on simulation test results. Although the soil model used in simulations exhibits ideal and uniform physical properties, actual field operations reveal that soil subsides after pit excavation, with significant variations in moisture content and compaction levels, resulting in reduced effective planting depth. Consequently, field trials adopted a slightly higher installation height, with the pit-digging shovel's installation height set at 55 mm, and the distance between the pit-digging shovel and the suspended-cup planter set at 550 mm, and the operating speed maintained at 0.4 m/s. Each trial section exceeded 100 m in length, and the machine's average operating speed was maintained at the prescribed trial speed. The pit-digging depth test was first conducted. After each pit-digging operation, the first 10 pits and last 10 pits were excluded, and 100 consecutive pits were measured starting from a random position within the remaining interval.

When the depth fell within the range of 90–120 mm, it was considered to meet the pit-digging depth qualification standard.

Subsequently, transplanting trials were performed. After each transplanting operation, the first 10 seedlings and last 10 seedlings were excluded, and transplanting was considered to meet the centering qualification standard when the positional error between the transplanting point and the pit center was within 20 mm. The calculation methods for the pit-digging depth qualification rate Y_1 and the transplanting centering qualification rate Y_2 are as (2) and (3):

$$Y_1 = \frac{M_t}{m} \times 100\% \quad (2)$$

$$Y_2 = \frac{N_j}{n} \times 100\% \quad (3)$$

where M_t is the total number of pits that are qualified in the pit, N_j is the in order to determine the number of tobacco seedlings that are qualified transplanting centering accuracy, m is the number of total pits to be measured; n is the total number of smoke seedlings measured.

3. Results and Discussion

Following the test method, three repeated trials were conducted for both the pit-forming and transplanting tests.

Statistical analysis shows that the pit-digging depth qualification rate reached 98.3% (Table 8) and the transplanting centering qualification rate reached 97.7% (Table 9), both satisfying the requirements of tobacco transplanting machines. These qualification rates are considered sufficient to meet agronomic requirements and demonstrate good field application potential. These results also verify the reliability of the coupled pit-digging, transplanting, and tobacco-ridge model.

Table 8. Field test results of drilling depth

Serial number	Quantity (piece)	Qualification rate of physical experiments (%)	Qualification rate of simulation experiments (%)
The first group	100	98	98.3
The second group	100	99	
The third group	100	98	
Standard deviation	0	0.47	

Table 9. Results of neutral field test on transplanting

Serial number	Quantity (piece)	Neutral qualification rate of physical experiments (%)	Neutral qualification rate of simulation experiments (%)
The fourth group	100	98	97.7
The fifth group	100	98	
The sixth group	100	97	
Standard deviation	0	0.58	

By comparing the simulation and experimental results, the relative errors between the simulated and measured values were 1.23% and 1.34%, respectively, which verifies the reliability of the simulation. However, the field experiments were only conducted at a single experimental site with a single soil type in Henan Province. Therefore, the findings may be affected by local soil texture, spatial and temporal variability of soil moisture, and topographic conditions. The transferability and universality of the optimized parameters under different climatic, soil, and topographic conditions still need further validation. In particular, the performance of the optimized parameters—an installation height of 55 mm, a horizontal installation distance of 550 mm, and an operating speed of 0.40 m/s—may be influenced by variations in soil moisture content, ridge morphology, and field topography.

Consequently, the transferability and universality of these optimal parameters under different climatic, soil, and topographic conditions still require further validation. Future research should therefore carry out multi-site experiments across diverse soil types

and ecological zones, systematically examining the effects of these factors to improve the applicability and reliability of the proposed parameters.

4. Conclusions

In response to the identified limitations of conventional tobacco transplanting mechanisms—namely, the separation of pit-digging and transplanting operations, poor adjustability, and lack of systematic parameter matching—this study proposes an integrated and systematically optimized solution.

The following conclusions are drawn from the design, simulation, and experimental validation:

(1) The traction-type tobacco transplanter innovatively integrates a shovel-type pit-digging mechanism with a suspended-cup transplanting unit, enabling synchronized pit excavation and seedling placement in a single forward pass. Notably, the pit-digging mechanism features independently adjustable installation height and horizontal distance, which provide a practical and flexible

means to regulate pit depth and transplanting centering accuracy according to varying field conditions. This integrated and adjustable design effectively meets the agronomic requirements for tobacco transplantation in plain-growing regions, offering a novel solution to improve operational coordination and transplanting quality.

(2) Using coupled EDEM-RecurDyn simulation methods, a pit-digging, planting device-tobacco-ridge coupling model was established and utilized to simulate pit-digging and transplanting operations. Simulation analysis revealed that the planting trajectory follows a water-drop-shaped path. The research established the functional relationships between the lowest points of the pit-digging shovel and the suspended-cup planter, and clarified how horizontal installation distance and shovel mounting height influence pit depth and plant spacing. These findings improve tobacco transplantation quality and provide a systematic design methodology for coupled traction-type tobacco transplanting mechanisms.

(3) Field testing validated the simulation model and prototype design. Optimal transplanting performance was achieved with the following parameters: operating speed of 0.4 m/s, pit-digging shovel mounting height of 55 mm, and horizontal installation distance of 550 mm between the pit-digging shovel and suspended-cup planter. Under these conditions, the transplanter achieved a transplanting efficiency of 46.3 plants/min with high-quality seedling placement. The relative errors between simulation and field test results for Y_1 and Y_2 were 1.23% and 1.34%, which verify the validity and reliability of the simulation model.

(4) Field testing demonstrated that soil conditions and soil moisture content significantly influence pit-digging performance. Prior to transplanting operations on new sites, preliminary field trials are recommended to calibrate machine parameters to local soil conditions. The adjustment procedure involves two sequential steps: (1) adjust seedling planting depth using the ground-wheel mechanism, (2) fine-tune the horizontal distance between the pit-digging shovel and suspended-cup planter by adjusting the pit-digging shovel mounting position. These sequential adjustments ensure optimal transplanting performance under varying soil conditions.

Funding

This research was funded by Henan Tobacco Company Major Science and Technology Project, with grant number 2023410000240028, and State key laboratory of intelligent agricultural power equipment open project "Hydraulic control system design of hydraulic drive track-laying vehicle", with grant number SKLIAPE 202401.

Acknowledgments

The authors would like to thank the technical editor and anonymous reviewers for their constructive comments and suggestions related to this study.

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