SIMULATION ANALYSIS AND EXPERIMENTAL STUDY OF THE PLANTING MECHANISM OF A FULLY AUTOMATIC STRAWBERRY TRANSPLANTER
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草莓全自动移栽机栽植机构仿真分析与试验研究

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ABSTRACT

To improve the efficiency and standardization of strawberry production and to address the low automation level and unstable planting quality of existing transplanters, this study developed a fully automatic strawberry transplanter and optimized its core planting mechanism. The machine and planting device were structurally designed based on the biological characteristics of strawberry seedling plugs and agronomic requirements, with the aim of enhancing seedling uprightness and overall operational performance. A coupled DEM–MBD simulation approach was applied to establish a dynamic interaction model among the planter, soil, and seedling plugs within the EDEM–RecurDyn co-simulation environment. Using seedling uprightness as the primary performance indicator, single-factor experiments were conducted to clarify the effects of opening angle, planting depth, and planting frequency on planting quality. A three-factor, three-level Box–Behnken design was then used to optimize the parameters, and an optimal combination of a 27° opening angle, 130 mm planting depth, and 48 plants/min planting frequency was obtained, corresponding to a predicted uprightness of 86.72°. Field validation showed that the planting qualification rate remained consistently above 90% and the coefficient of variation of plant spacing was below 4%, outperforming current operational standards. These results confirmed the efficiency and reliability of the proposed planting mechanism and provided a practical foundation for developing precision transplanting equipment for protected horticultural crops using coupled simulation and parameter optimization.

摘要

为提高草莓种植的机械化与标准化水平，针对现有移栽装备自动化程度低、栽植质量不稳定等问题，本研究研制了一款全自动草莓移栽机并对其栽植装置进行优化设计。依据草莓钵苗的生物学特性与农艺需求完成整机与栽植装置构型设计，以提升钵苗直立度和作业性能为目标。采用DEM–MBD耦合仿真方法，在EDEM–RecurDyn环境下构建栽植器、土壤与钵苗的动态作用模型，并通过单因素试验分析开口角度、入土深度和栽植频率对栽植直立度的影响规律。进一步利用三因素三水平BBD响应面法进行参数优化，确定最优参数组合为开口角度27°、入土深度130 mm、栽植频率48株/min，对应仿真预测直立度为86.72°。田间试验表明栽植合格率稳定在90%以上，株距变异系数小于4%，显著优于现行作业水平。本研究验证了装置的高效性与可靠性，为设施作物精准移栽装备研发提供了参考。

INTRODUCTION

Strawberry is a perennial herbaceous plant of the Rosaceae family. Its pleasant flavor, rich nutritional value, and high economic importance make it one of the most significant berry crops worldwide. The global annual strawberry output is approximately 8.783 million tons. China, the world’s leading producer, accounts for 29.8% of the total planting area and 35.6% of global production, with an industry value exceeding 60 billion RMB *(Yang et al., 2024; Ilari et al., 2021; Zhou et al., 2025)*. As production scales continue to expand, the heavy reliance on manual labor has become increasingly problematic, and traditional labor-intensive cultivation practices can no longer meet the growing demands of the industry. In the planting stage in particular, the fragmented cultivation patterns, low level of operational standardization, and lack of unified technical specifications make the realization of fully mechanized strawberry production an urgent necessity *(Liu et al., 2022; Yu et al., 2022; Jiang et al., 2025)*.

As the core component of transplanting equipment, the planting mechanism directly affects key quality indicators such as seedling uprightness, exposure rate, and plant-spacing uniformity *(Na et al., 2022; Ma et al., 2025)*. Internationally, *Gutiérrez et al., (2009),* developed a bare-root strawberry transplanter that performs film cutting and seedling insertion through zero-speed contact; however, its high manufacturing cost and reliance on customized plug trays limit its suitability for small-scale production. In China, *Jin et al., (2024),* proposed a multi-blade duckbill planting mechanism. *Liu., (2019),* compared the hole-forming performance of duckbill planters with different cross-sectional shapes; and *Li et al., (2022),* investigated a cam–rocker-based mechanism to improve planting quality. However, most existing studies concentrate on structural refinement and generally lack systematic simulation analyses of the dynamic interactions among the planter, soil, and seedling plug. In particular, existing studies rarely provide a coupled DEM–MBD framework to quantitatively describe the dynamic interactions among the planting mechanism, soil, and seedling plug during high-frequency transplanting.

Research on automated transplanting equipment for strawberry production remains underdeveloped, and many existing machines still rely on manual participation during seedling picking and placement, which significantly restricts operational efficiency. Therefore, developing a fully automated transplanting system that integrates seedling feeding, picking, placement, and planting has become an urgent requirement for achieving efficient and standardized strawberry cultivation. Within such systems, the planting mechanism functions as the key execution unit, and its performance directly determines essential quality indicators such as seedling uprightness, exposure rate, and plant-spacing uniformity. Although previous studies have proposed multi-blade duckbill mechanisms and cam–rocker configurations, systematic and in-depth simulation analyses of the coupling mechanism among the planter, soil, and seedling plug during dynamic transplanting remain limited. This study developed a fully automatic strawberry transplanter and proposed an EDEM–RecurDyn co-simulation framework to analyze the dynamic coupling among the planting mechanism, soil, and seedling plugs. Key operating parameters were optimized based on seedling uprightness using single-factor analysis and response surface methodology. Field trials were performed to verify planting quality and operational stability.

MATERIALS AND METHODS

Design and Working Principle of the Planting Mechanism for a Strawberry Transplanting Machine

The fully automatic strawberry transplanter was composed of several major components, including the seedling tray conveyor, seedling picking–placing mechanism, planting mechanism, chassis, and electrical control box. The planting mechanism was primarily composed of the duckbill planters, duckbill planter connecting plate, duckbill planter fixing plate, connecting rods, opening–closing cylinder, vertical rodless cylinder, and guide bearings. A schematic diagram of the planting mechanism was shown in Figure 1.

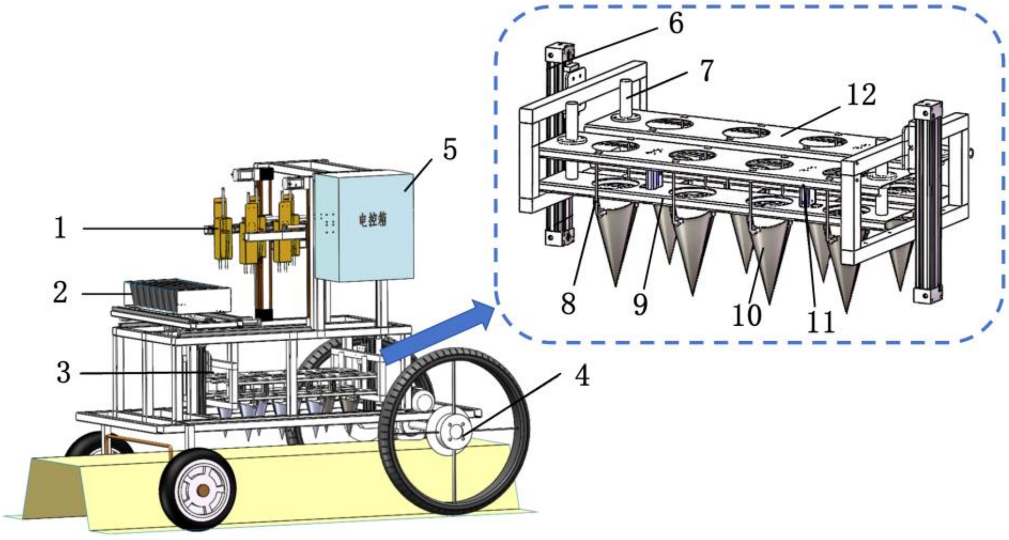
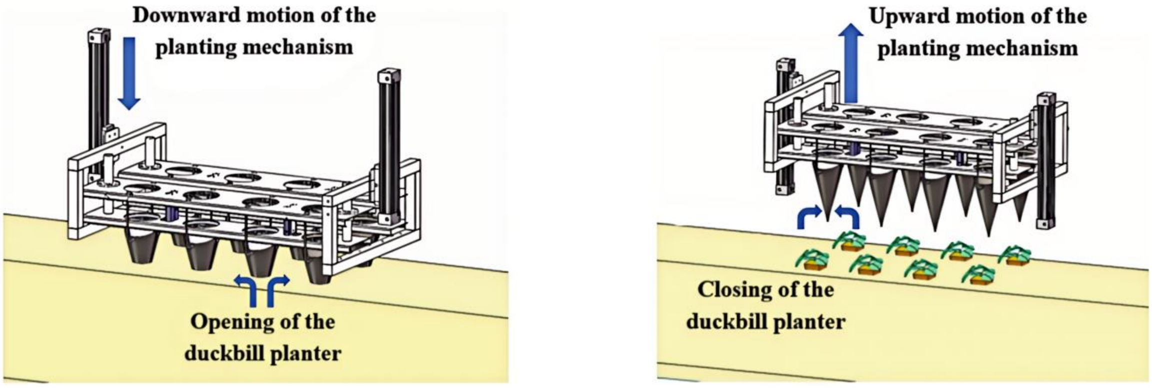


Fig. 1 - Schematic diagram of the planting mechanism of a strawberry transplanter

1-Seedling picking–placing mechanism; 2-Seedling tray conveyor; 3-Planting mechanism; 4-Chassis; 5-Electrical control box. 6-Vertical rodless cylinder; 7-Guide bearing; 8-Duckbill connecting rod; 9-Duckbill fixing plate; 10-Duckbill planter; 11-Opening–closing cylinder; 12-Duckbill planter connecting plate.

The operating standard of the planting mechanism requires the planter to accurately accomplish point-to-point actions for receiving, delivering, and planting seedlings. Based on existing planting mechanisms and agronomic requirements for strawberry cultivation, the design of the planting mechanism must satisfy the following criteria: (1) The mechanism must handle appropriately aged potted strawberry seedlings. (2) The seedling drop position must be accurately controlled, and occurrences of seedlings being hung or pinched must be strictly avoided. (3) The working process must synchronously integrate both cavity formation and transplanting operations. (4) The effective planting depth must be maintained within the range of 100–120 mm. (5) During planting, the opening–closing operation of the planter must be precise, with accurate opening width to ensure no missed seedlings during receiving and no blockage during planting.

The vertical rodless cylinder drives the eight duckbill planters to move vertically. After the picking claws drop the seedling plug into the duckbill planters, the vertical rodless cylinder moves the entire planting mechanism downward. Once the duckbill planters penetrate the soil, the opening–closing cylinder pushes the duckbill planter connecting plate upward, causing the duckbill planters to open and allowing the seedling plug to fall into the soil, as shown in Figure 2(a). After the seedling plug is planted, the vertical rodless cylinder lifts the planting mechanism upward. When the planters rise above the strawberry seedling's stem and leaves, the opening–closing cylinder lowers the connecting plate, causing the duckbill planters to close and completing one planting cycle, as shown in Figure 2(b).



(a) (b)

Fig. 2 - Working process of the planting mechanism

(a) Seedling Planting Process. (b) Seedling Planting Completed.

Analysis of Soil Penetration Resistance of the Duckbill Planter

Soil exhibited the ability to resist deformation and restore its shape when subjected to external forces, which manifests as the resistance acting on the duckbill planter during soil failure. The resistance encountered by the duckbill planter during soil penetration primarily arose from friction between the planter and soil, as well as the soil's cohesive force, adhesive force, and compressive resistance to mechanical disruption *(Guo et al., 2011; Abhijit et al., 2022)*. Taking a conical duckbill planter as an example, a theoretical analysis of soil penetration resistance during transplanting is performed. Without affecting the analytical results, the duckbill planter is simplified, and a force analysis is conducted on the soil-contacting component of the planting mechanism, as shown in Figure 3. The penetration resistance *P* of the duckbill planter and the soil penetration resistance *F* are an action–reaction pair, equal in magnitude and opposite in direction.

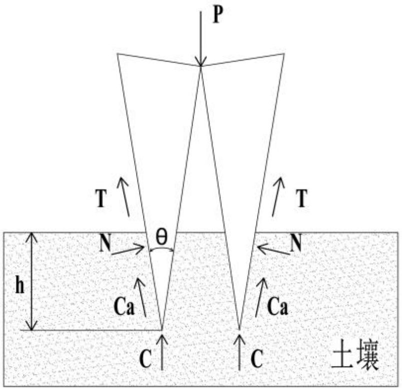


Fig. 3 - Analysis of soil penetration resistance of the duckbill planter

The resistance P acting on the duckbill planter during soil penetration is calculated using Equation (1).

$$P = 2 \times (T \cos\theta + N \sin\theta + C_a \cos\theta \, S + C) \tag{1}$$

where: T represents the friction force on the planter's lateral surface (N), N represents the normal force on the lateral surface(N), C represents the cohesive force acting on the contact surface between the duckbill planter and soil (N), C_a represents the tangential adhesion coefficient on the lateral surface of the duckbill planter (N/m²) and P represents the represents the penetration resistance of the duckbill planter (N).

$$\begin{cases} T = \sigma\mu S \\ N = \sigma S \end{cases} \tag{2}$$

where: σ - unconfined compressive strength of the soil (N/m²); μ - friction coefficient between the soil and the duckbill planter.

For the analytical derivation, the duckbill planter was simplified as a symmetric wedge, and the lateral soil–planter contact surface was approximated as a triangular area whose effective width increased linearly with the penetration depth *h* according to the opening angle *θ*.

The lateral surface area *S* of the duckbill planter is:

$$S = \tan\theta h^2 \tag{3}$$

where h is the penetration depth (m), θ is the opening angle (°), and S is the effective contact area (m^2). All variables in the analytical equations were expressed in SI units; in particular, h was consistently expressed in meters (m) throughout the derivations.

From the above derivation, the soil penetration resistance *F* acting on the duckbill planter can be expressed as:

$$F = 2\tan\theta h^2[\sigma(\mu\cos\theta + \sin\theta) + C_a\cos\theta] + 2C \tag{4}$$

During soil penetration, the resistance *F* experienced by the duckbill planter exhibits a quadratic relationship with the penetration depth *h*, and the resistance increases continuously as the penetration depth becomes greater. Therefore, within the required planting depth range for strawberry cultivation, a relatively smaller planting depth should be selected whenever possible.

Simulation Analysis of the Planting Process Based on EDEM–RecurDyn Co-simulation

The planting mechanism contained four planters on each side, and since all planters operate under the same working principle, only one planter on each side needs to be analyzed. The model was simplified in *SolidWorks*, and based on the actual motion characteristics of the planting mechanism, appropriate motion pairs were added in *RecurDyn*. The planting operation was then simulated using the *Simulation* module *(Hou et al., 2025; Zhang et al., 2022)*.

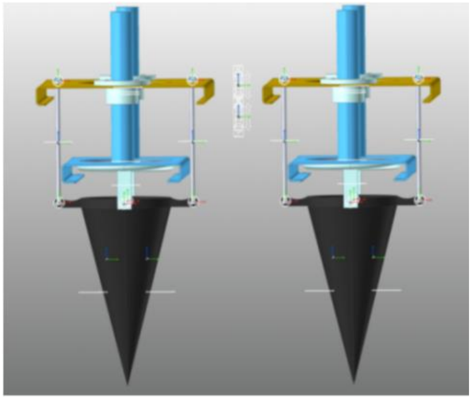


Fig. 4 - RecurDyn simplified model and dynamic parameter settings

Contact between soil particles was modeled using the *Hertz–Mindlin JKR* model. Contact between substrates was modeled using the *Hertz–Mindlin JKR* model*,* while interactions between the duckbill planter and the soil, as well as between the planter and the strawberry seedling plug, were modeled using the *Hertz–Mindlin (no slip)* model *(Zeng et al., 2024; Zhang et al., 2022)*. After selecting the appropriate contact models, the intrinsic material parameters, contact parameters, and cohesive parameters were further defined. These key parameters were determined with reference to previous studies and related data *(Song et al., 2022; Tian et al., 2021; Kang et al., 2025)*. The simulation parameters are listed in Table 1.

Table 1

Main parameters for the discrete element simulation

Object	Parameter	Value
Soil particles	Density (kg/m³)	1452
	Poisson's ratio	0.42
	Shear modulus (Pa)	1e+06
Soil–soil interaction	Static friction coefficient	0.4
	Dynamic friction coefficient	0.3
	Restitution coefficient	0.45
	JKR surface energy/(J/m^2)	0.67
Soil–seedling plug interaction	Static friction coefficient	0.84
	Dynamic friction coefficient	0.35
	Restitution coefficient	0.37
Soil–planter interaction	Static friction coefficient	0.85
	Dynamic friction coefficient	0.13
	Restitution coefficient	0.35
Planter–seedling plug interaction	Static friction coefficient	0.79
	Dynamic friction coefficient	0.28
	Restitution coefficient	0.21
Substrate–substrate	Static friction coefficient	0.65
	Dynamic friction coefficient	0.345
	Restitution coefficient	0.2
	JKR surface energy/(J/m^2)	3.5

A soil trough model (length 100 mm, upper width 500 mm, lower width 700 mm, height 250 mm) was built in *SolidWorks* and imported into *EDEM*, where a particle factory was used to generate the soil particle model.

The complete transplanting operation of the duckbill planting mechanism was analyzed using *RecurDyn* and *EDEM*. A co-simulation was performed to examine the sequence in which the planting mechanism penetrates the soil, plants the potted strawberry seedlings, and exits the soil. The simulation model of the planting operation is shown in Figure 6.

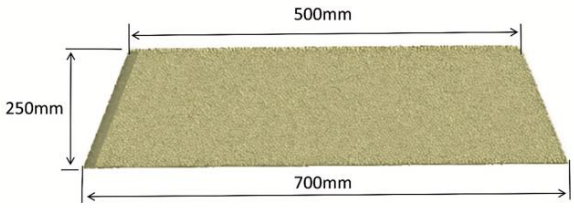


Fig. 5 - Soil test trough

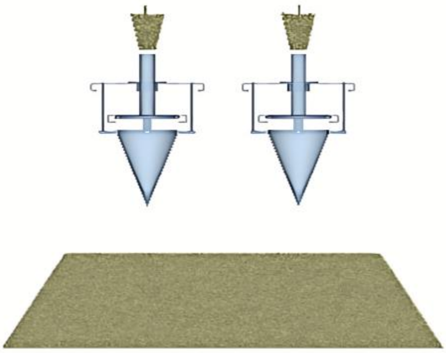


Fig. 6 - Simulation model of the planter–soil interaction

Planting Experiment

The field transplanting performance test was conducted at the Sujiatun experimental field in Shenyang. The prototype of the strawberry transplanting machine is shown in Figure 7. Rotary tillage and ridge formation were completed beforehand. The ridge dimensions were configured according to DB13/T 2749-2018 *Specifications for High-Ridge Film-Mulching Transplanting of Strawberry Plug Seedlings*, with a ridge height of 25 cm, a bottom width of 65 cm, and a top width of 50 cm. The experiment used strawberry plug seedlings from a 32-cell tray. Each cell measured 60 mm at the upper diameter, 28 mm at the lower diameter, and 110 mm in height. The experiment was repeated five times, with 64 strawberry plug seedlings selected for each trial. The seedlings were approximately eight weeks old, and their growth condition is shown in Figure 8.

Fig. 7 - Experimental prototype

Fig. 8 - Strawberry seedling plug

The primary objective of the experiment was to evaluate the planting performance of the fully automatic strawberry transplanter prototype. After optimizing all operational parameters of the machine, a comprehensive performance test was conducted. The test conditions were configured as follows: operating speed of 0.3 m/s, a planting frequency of 48 plants/min corresponding to the desired plant spacing, and a planting depth of 130 mm. A five-replicate experimental design was adopted. In each trial, two trays—containing a total of 64 seedlings—were transplanted continuously to assess system stability and planting quality. The planting results and plant spacing measurements of the strawberry seedling plugs are shown in Figure 9.

(a) **(b)**

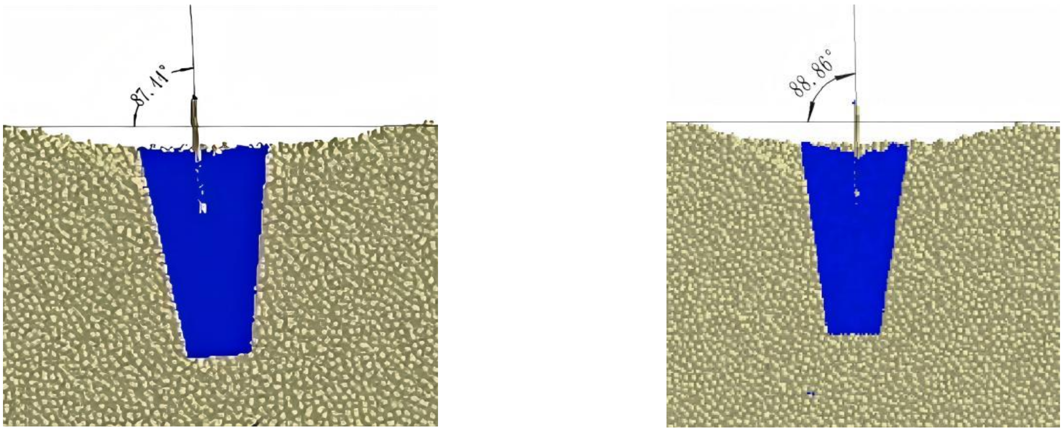
Fig. 9 - Planting effect and plant spacing measurement

(a) Planting effect; (b) Plant spacing measurement.

RESULTS

Single-factor Experiment and Analysis

Seedling uprightness (Figure 10) was one of the key indicators used to evaluate the transplanting quality of potted seedlings. The angle α between the stem of the potted strawberry seedling and the horizontal ground was defined as the uprightness angle. After each simulation, this angle was measured; the closer α was to 90°, the better the seedling uprightness. Seedling uprightness was classified into three levels: lodging, qualified, and excellent. The classification criteria are as follows: ≤45° indicates lodging, 45°–70° indicates qualified performance, and >70° indicates excellent uprightness.



(a) **(b)**

Fig. 10 - Measurement of seedling uprightness angle

To analyze how different parameter settings influence the planting quality of the duckbill planting mechanism, this study selected the opening angle, planting depth, and planting frequency as influencing factors, with seedling uprightness as the evaluation index. A single-factor experiment was conducted, and the experimental factors and levels are listed in Table 2.

Table 2

Experimental factors and levels

Level	Opening angle（°）	Planting depth（mm）	Planting frequency (plants/min)
1	21	110	32
2	24	120	40
3	27	130	48
4	30	140	56
5	33	150	64

Based on existing studies and related literature, the parameter ranges selected for the single-factor experiments were as follows: an opening angle of 21°–33°, a planting depth of 110–150 mm, and a planting frequency of 32–64 plants/min. For the simulation experiments, the parameter combination used was an opening angle of 27°, a planting depth of 130 mm, and a planting frequency of 48 plants/min. In each simulation run, two factors were kept constant while the remaining one was varied to investigate how each of the three single factors influences seedling uprightness.

(1) Influence of Opening Angle on Seedling Uprightness

To investigate the effect of the duckbill opening angle on seedling uprightness during planting, simulation experiments were conducted using a planting depth of 130 mm and a planting frequency of 48 plants/min. The opening angles tested were 21°, 24°, 27°, 30°, and 33°. After each simulation, seedling uprightness was measured, and the results are shown in Figure 11(a).

If the opening angle is too small, seedling pinching may occur, preventing the seedling plug from being properly released into the soil. Conversely, if the opening angle is too large, soil disturbance increases, the cavity opening becomes enlarged, and soil backflow is slowed, which ultimately reduces seedling uprightness. Based on a comprehensive assessment of planting quality, opening angles of 24°, 27°, and 30° were selected as the recommended range for structural parameter optimization.

(2) Influence of Planting Depth on Seedling Uprightness

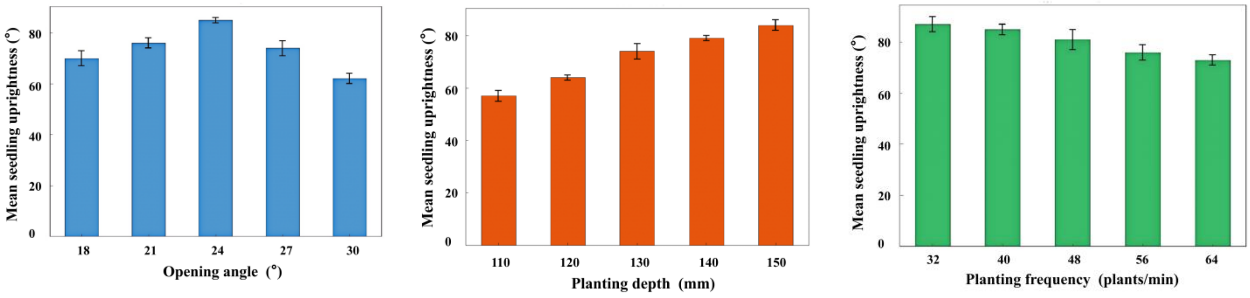
To investigate the effect of planting depth on seedling uprightness during transplanting, simulation experiments were conducted using an opening angle of 27° and a planting frequency of 48 plants/min. The tested planting depths were 110 mm, 120 mm, 130 mm, 140 mm, and 150 mm. After each simulation, seedling uprightness was measured, and the results are shown in Figure 11(b).

As the planting depth increases, seedling uprightness gradually improves. However, strawberry transplanting requires that the crown of the plant not be buried. Therefore, planting depths of 120 mm, 130 mm, and 140 mm were selected as the recommended range for subsequent structural parameter optimization.

(3) Influence of Planting Frequency on Seedling Uprightness

To investigate the effect of planting frequency on seedling uprightness during the transplanting process, simulation experiments were conducted using an opening angle of 27° and a planting depth of 130 mm. The tested planting frequencies were 32, 40, 48, 56, and 64 plants/min. After each simulation, seedling uprightness was measured, and the results are shown in Figure 11(c).

As the planting frequency increases, seedling uprightness progressively deteriorates. This is because a higher planting frequency shortens the operating time of the duckbill planter, potentially causing the seedling plug to be released before it stabilizes or before the soil has sufficient time to wrap and secure it, thereby reducing uprightness. Considering overall planting quality, planting frequencies of 88 plants/min, 48 plants/min, and 104 plants/min were selected as the recommended range for subsequent structural parameter optimization.



(a) (b) (c)

Fig. 11 - Results of the single-factor simulation

(a) Simulation experiment of opening angle. (b) Simulation experiment of planting depth.
(c) Simulation experiment of planting frequency.

Orthogonal Experimental Design and Result Analysis

Based on the single-factor simulation experiments, a three-factor, three-level response surface experiment was conducted. The coded levels of each factor are presented in Table 3. Through experimental analysis, the priority ranking of influencing factors on seedling uprightness was obtained, along with the optimal parameter combination for the planting mechanism during transplanting operations.

Table 3

Coded levels of experimental factors

Level	Factors		
	X1: Opening angle (°)	**X2: Planting depth (mm)**	**X3: Planting frequency (plants·min⁻¹)**
-1	21°	120	40
0	24°	130	48
1	27°	140	56

According to the principles of the Box–Behnken Design (BBD), a three-factor, three-level planting simulation experiment was designed *(Lai et al., 2020; Yi et al., 2020; Yu et al., 2020)*. A total of 17 simulation runs were conducted, including 5 center-point tests. The experimental design and results are presented in Table 4.

Table 4

Experimental design and results

No	Factors			Evaluation index
	X1	**X2**	**X3**	**R (°)**
1	24	120	48	67.34
2	30	120	48	71.85
3	24	140	48	82.75
4	30	140	48	75.68
5	24	130	40	78.08
6	30	130	40	83.58
7	24	130	56	84.77
8	30	130	56	72.55
9	27	120	40	80.66
10	27	140	40	87.97
11	27	120	56	78.43
12	27	140	56	84.34
13	27	130	48	87.75
14	27	130	48	86.96
15	27	130	48	87.44
16	27	130	48	86.92
17	27	130	48	85.65

Based on the experimental data, the regression model describing the relationship between seedling uprightness R and the factors—opening angle X_1, planting depth X_2, and planting frequency X_3 is expressed as follows:

$$\begin{aligned}\hat{R} = 86.94 - 1.16X_1 + 4.06X_2 - 1.27X_3 - 2.89X_1X_2 - 4.43X_1X_3 - 0.35X_2X_3 \\ -7.82X_1^2 - 4.72X_2^2 + 0.623X_3^2\end{aligned} \tag{5}$$

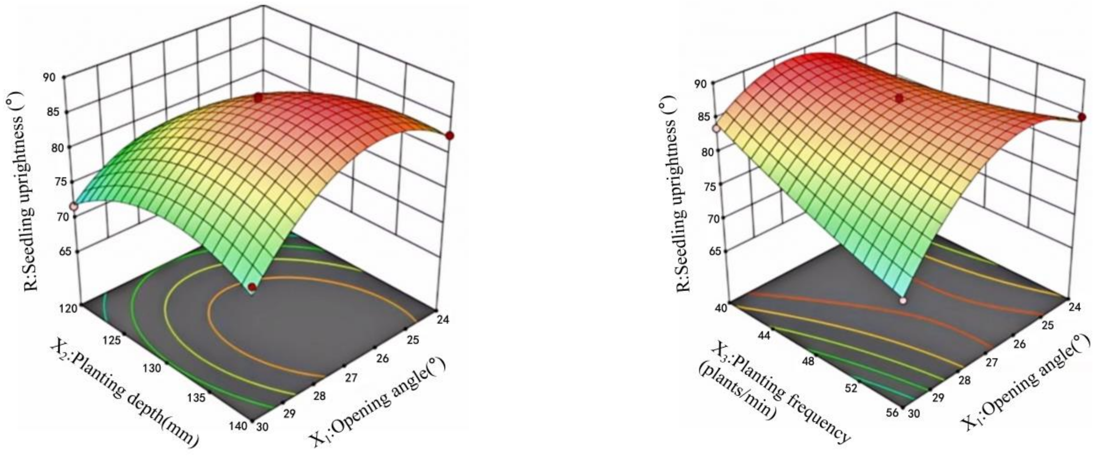
The analysis of variance (ANOVA) for the fitting model of seedling uprightness, including the P-values of each factor and the ANOVA results of the multiple regression model, is presented in Table 5. As shown in the table, the P-value of the seedling uprightness fitting model is less than 0.0001, indicating extremely high significance and good regression performance. The signal-to-noise ratio of the regression equation is 22.23, which is greater than 4.0. A signal-to-noise ratio exceeding 4.0 is commonly regarded as evidence of a good fit between the model and the experimental data. In summary, the response surface quadratic regression model demonstrates a satisfactory degree of fit.

Table 5

Regression Model Variance Analysis

Source of variance	Sum of squares	Degrees of freedom	Mean square	F-value	P-value
Model	636.69	9	70.74	51.84	<0.0001**
X_1	10.76	1	10.76	7.89	0.0262*
X_2	131.71	1	131.71	96.51	<0.0001**
X_3	13.00	1	13.00	9.53	0.0176*
$X_1 X_2$	33.52	1	33.52	24.56	0.0016**
$X_1 X_3$	78.50	1	78.50	57.52	0.0001**
$X_2 X_3$	0.49	1	0.49	0.3591	0.5679
X_1^2	257.62	1	257.62	188.77	<0.0001**
X_2^2	93.68	1	93.68	68.65	<0.0001**
X_3^2	1.63	1	1.63	1.20	0.3100
Residual	9.55	7	1.36		
Lack of fit	6.98	3	2.33	3.62	0.1229
Pure error	2.57	4	0.6427		
Total variation	646.24	16			

The first-order terms X_1 and X_2, the interaction terms X_1X_2 and X_1X_3, and the quadratic terms X_1^2 and X_2^2 all exhibited highly significant effects (P < 0.01) on the response. The first-order terms X_1 and X_3 showed significant effects at the 0.01 < P < 0.05 level. According to the F-test results, the order of influence on seedling uprightness is $X_2 > X_3 > X_1$, that is, planting depth > planting frequency > opening angle.



(a) **(b)**

Fig. 12 - Influence of each factor on seedling uprightness

(a) Opening angle and planting depth. (b) Opening angle and planting frequency.

Figure 12 illustrates the interactive effects of the three factors on seedling uprightness. As shown in the figure, when the planting depth is held constant, seedling uprightness increases initially and then decreases as the opening angle increases. When the opening angle is held constant, seedling uprightness decreases progressively as the planting frequency increases. When the planting frequency is fixed, seedling uprightness first increases and then decreases with increasing opening angle. The interaction terms X_1X_2 and X_1X_3 exert significant effects on seedling uprightness ($P < 0.05$), whereas the interaction between X_2X_3 is not significant ($P > 0.05$), indicating a relatively minor influence. According to the above data and interaction plots, the influence ranking of the two-factor interaction terms on seedling uprightness is ($X_1X_3 > X_1X_2 > X_2X_3$).

To ensure a high level of seedling uprightness, the optimal combination of influencing factors was determined within the specified constraints, providing parameter guidance for subsequent field experiments. Using the opening angle of the planter, planting depth, and planting frequency as optimization variables, the parameter optimization was carried out, and the mathematical optimization model was established as shown in Equation (6):

$$\max R\left(X_1, X_2, X_3\right) = R$$
$$\begin{cases} 24 \le X_1 \le 30 \\ 120 \le X_2 \le 140 \\ 40 \le X_3 \le 56 \end{cases} \tag{6}$$

where R is the predicted seedling uprightness obtained from Eq. (5) (°); X_1 is the opening angle of the planter (°); X_2 is the planting depth (mm); and X_3 is the planting frequency (plants·min^{-1}). The ranges of X_1, X_2, and X_3 in Eq. (6) corresponded to the experimental factor levels used in the Box–Behnken design.

The optimization results yielded the optimal parameter combination of an opening angle of 27.020°, a planting depth of 129.657 mm, and a planting frequency of 48.439 plants/min. Considering the feasibility of the operational parameters, the optimal values were adjusted to an opening angle of 27°, a planting depth of 130 mm, and a planting frequency of 48 plants/min. Under this parameter combination, the resulting seedling uprightness was 86.722°.

Analysis of field tests results

In this experiment, the planting qualified rate was calculated based on the counts of missed plants, lodged plants, buried plants, replanted plants, exposed plants, and injured plants. Additionally, plant spacing measurements were taken from 15 groups of strawberry seedlings to compute the coefficient of variation of plant spacing. These data were used to verify whether the operational performance of the strawberry transplanter met the design requirements. The measured results were statistically analyzed, and the performance indicators are shown in Table 6.

Table 6

Performance indicators of the planting test

Test No	Number of missed plants	Number of lodged plants	Number of buried plants	Number of replanted plants	Number of exposed plants	Number of injured plants	Planting qualified rate (%)
1	0	0	2	0	0	0	96.88
2	1	1	0	1	2	0	92.18
3	0	2	0	0	0	1	95.31
4	0	0	1	0	1	2	93.75
5	2	1	1	2	0	0	90.63
Mean ± SD	0.60±0.89	0.80±0.84	0.80±0.84	0.6.±0.89	0.60±0.89	0.60±0.89	93.75±2.47

The planting qualified rate P was calculated as:

$$P(\%) = 100\% - (\eta_1 + \eta_2 + \eta_3 + \eta_4 + \eta_5 + \eta_6) \tag{6}$$

where $\eta_1 - \eta_6$ represent the missed, lodged, buried, replanted, exposed, and injured rates, respectively, and each rate was defined as $\eta_i = \frac{N_i}{N}$, with N being the total number of seedlings in each test.

Analysis of the planting performance indicators shows that the strawberry transplanter developed in this study has achieved the intended research objectives. The planting qualified rate exceeded 90% in all test groups, indicating the high reliability of the transplanter.

The consistently high qualified rate demonstrates stable operational quality and confirms that the system reliability meets the design requirements, thereby fulfilling the anticipated technical specifications.

CONCLUSIONS

The complete working process of the planting mechanism was simulated using an *EDEM–RecurDyn* co-simulation model, and the key parameters affecting seedling uprightness were quantitatively identified. Single-factor co-simulation experiments were conducted to analyze the effects of three parameters—opening angle, planting depth, and planting frequency—on seedling uprightness. A three-factor, three-level Box–Behnken Design (BBD) experiment was performed with maximum seedling uprightness as the optimization objective. The optimal combination was determined to be an opening angle of 27°, a planting depth of 130 mm, and a planting frequency of 48 plants/min, resulting in a seedling uprightness of 86.72°.

A field validation test using strawberry seedling plug was carried out to evaluate the actual working performance of the prototype. The results showed that the relative error between the average measured plant spacing and the theoretical plant spacing was 3.26%, and the coefficient of variation of plant spacing was 3.57%. The planting qualified rate remained above 90% in all trials. Overall, the field results were consistent with the optimization outcome, indicating that the selected parameter combination maintained stable transplanting quality and spacing uniformity.

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