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Design and Experimental Research on the Orientation Planting Device of Electric Strawberry Transplanting Machine

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Abstract: To address the agronomic requirements of greenhouse strawberry cultivation involving high-ridge planting, narrow row spacing, close plant spacing, and directional planting, this study developed a deep-planting directional transplanting device featuring a small cavity opening. The device consists of a servo motor-driven screw transmission mechanism for deep planting and a cam-swing-based directional clamping seedling-release mechanism, effectively solving the challenges of achieving sufficient planting depth and maintaining proper orientation during strawberry plug seedling transplantation. Through Box-Behnken experimental design, maintaining average cavity length of 139.3 mm within the qualified range. Furthermore, the optimized configuration achieved a minimal seedling deflection angle of 0.31°, meeting stringent directional planting standards. Field validation tests confirmed the device's superior performance, with planting qualification rates exceeding 90.56% and directional accuracy reaching 91.67%, thereby verifying the scientific validity and practical effectiveness of this electric strawberry transplanter's directional planting system design.

Keywords: Directional planting device, Hole-forming size, Simulation, Deflection angle of strawberry seedling pot.

1. Introduction

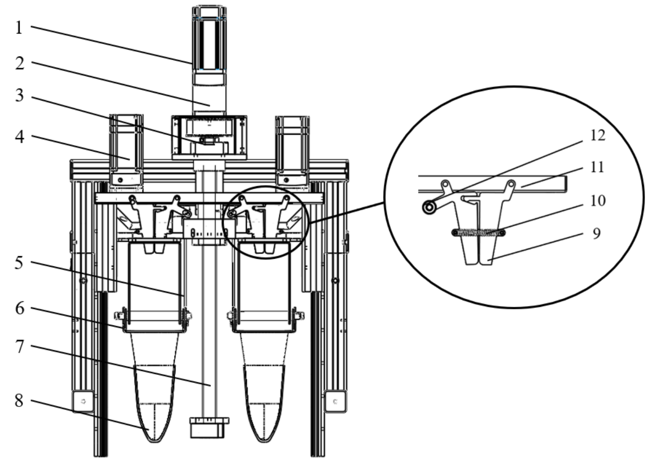
Strawberry, as a fruit crop with high economic value and precise cultivation management, imposes strict agronomic requirements during the transplanting process. For a long time, China has relied on traditional manual planting methods, which involve high labor intensity and low planting efficiency. There is an urgent need to introduce strawberry transplanters to improve agricultural planting efficiency and promote the transformation and upgrading of the agricultural industry. The strawberry seedling pots are relatively large in size and require deep planting. Additionally, the agronomic requirements primarily include oriented planting, deep planting without burying the heart, and shallow planting without exposing the roots. These factors place high demands on the transplanting device. Therefore, to ensure the quality of transplanting, it is necessary to optimize the key parameters of the transplanting device to achieve the best planting performance.

Currently, existing transplanting devices are primarily designed for vegetable plug seedlings and are mostly of the duckbill type. Strawberry seedlings are tall, have a large canopy spread, and exhibit typical characteristics of "large seedlings." Moreover, strawberry transplanting requires the arch back to face outward from the ridge. Existing vegetable plug seedling transplanters cannot be directly applied to strawberry planting. In response to the characteristics of strawberry seedling pots, relevant transplanters equipped with planting devices include the 948T strawberry transplanter manufactured by Mechanical Transplanter Company in the Netherlands [1]. This transplanter features a duckbill structure, where the duckbill closes during manual feeding of seedlings into the basket and opens to transplant the seedlings into the soil. The transplanter is suitable for double-row bare-root seedlings and strawberry pot transplanting but cannot operate independently, requiring a tractor for power. Meng Qingyu [2] et al. developed a greenhouse strawberry transplanter that uses a method of first opening a furrow and then picking and placing seedlings into the furrow for transplanting. Although an adjustable furrow opener and depth-limiting wheel system were employed to ensure "deep planting without burying the heart and shallow planting without exposing the roots" for strawberries, the symmetrical clamping mechanism caused the strawberry seedling pots to rotate randomly around the vertical axis during clamping, failing to ensure the stability of the arch back orientation.

Therefore, based on existing transplanting devices and the requirements of strawberry planting, this study designs an oriented duckbill planting device. The device uses a servo motor to drive a screw transmission mechanism, enabling linear planting motion for the deep planting of strawberry seedling pots. To meet the oriented planting requirements of strawberry seedlings, a multi-factor simulation analysis was conducted using the deflection angle of the strawberry seedling pot as the experimental response to obtain optimal parameters. Field experiments were performed to verify the planting qualification rate, planting hole dimensions, and deflection angle of the strawberry seedling pots for the optimized oriented planting device. The research results can provide a theoretical basis and technical reference for the design of oriented planting devices for electric strawberry transplanters.

2. Structure and Working Principle of the Oriented Planting Device

The oriented planting device is a key component of the electric strawberry transplanter, consisting of a planting mechanism and an oriented clamping and seedling release mechanism, as shown in Figure 1. The planting mechanism is primarily composed of a planting motor, a planting motor reducer, a duckbill opening and closing motor, a seedling feeding mechanism, a pull wire, a duckbill opening and closing rod, a screw mechanism, and a duckbill. The oriented clamping and seedling release mechanism mainly comprises a roller, a fixed plate, a spring, and a seedling pot oriented support plate.



1. Planting motor. 2. Planting motor reducer. 3. Synchronous belt transmission mechanisim. 4. Duckbill opening; and closing motor. 5. Pull wire. 6. Duckbill opening and closing rod. 7. Screw mechanism. 8.Duckbill. 9. Roller. 10. Fixed plate. 11. Spring. 12. Seedling pot oriented support plate

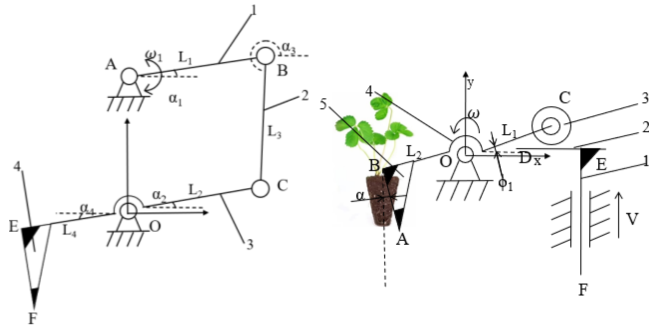
Figure 1. Schematic diagram of the planting mechanism

At the start of operation, strawberry seedlings are manually placed into the seedling pot oriented support plate. Subsequently, the planting motor drives the screw mechanism to lift the roller on the planting mechanism, opening the seedling pot oriented support plate. The strawberry seedling pot then drops into the duckbill. As the planting mechanism descends, the spring pulls the seedling pot oriented support plate closed. When the planting mechanism descends to the specified planting depth, the planting motor drives the mechanism to begin upward movement. Simultaneously, the duckbill opening and closing motor activates, opening the duckbill to a specified angle and maintaining it for a period of time. The seedling pot falls into the planting hole as the duckbill opens. Once the planting mechanism emerges from the soil over a certain distance, the duckbill begins to close under the action of the spring. Finally, as the planting mechanism moves upward and reaches the seedling receiving point again, the duckbill fully closes under the spring's action, completing the planting operation and preparing for the next planting cycle.

Kinematic diagrams of the planting mechanism and the oriented clamping and seedling release mechanism are shown in Figure 2.

Based on the designed four-link opening and closing planting mechanism, a kinematic diagram of the duckbill opening and closing motion is drawn [3]. Point E is the highest point of the duckbill planter, and the duckbill opening and closing swing link 3 is connected to the origin O via a revolute joint. Motor swing link 1 serves as the uniform-speed driving component, providing opening and closing power for the planting mechanism. Components 2, 3, and 4 are driven components, driving duckbill 4 to perform periodic circular oscillatory motion with a fixed trajectory.

Based on the designed cam-type oscillating opening and closing oriented seedling release mechanism, a kinematic diagram of the seedling release mechanism is drawn [7, 8]. Point A is the lowest point of the seedling support, and point B is the highest point of the seedling support. Rod 4 is the opening and closing swing link, and component 2, the opening and closing top plate, has a virtual constraint with roller 3. Component 1, the screw push rod, provides the opening and closing power for the seedling pot oriented support plate. Screw push rod 1 serves as the uniform-speed driving component, and rod 4 is the driven component, driving seedling pot oriented support plate 5 to perform periodic circular oscillatory motion with a fixed trajectory.



(a) Planting mechanism (b) Oriented clamping and seedling release mechanism

1. Motor swing link 2. Connecting rod 3. Duckbill opening and closing swing link 4. Right duckbill 5. Screw push rod 6. Top plate 7. Roller 8. Opening and closing swing link 9. Right seedling pot oriented support plate

α_1: Initial phase angle of crank ABα_2: Angular displacement of rod OCα_3: Angular displacement between rods AB and BCα_4: uckbill opening and closing angle of rod OEω_1: Angular velocity of rod ABϕ_1: Angular displacement of rod OCω: Angular velocity of rod BOCα: Opening and closing angle of seedling pot support plate

Figure 2. Schematic diagram

3. Kinematic Simulation Analysis of the Oriented Planting Motion of the Planting Mechanism

Since the opening and closing speed of the seedling pot oriented support plate, the opening and closing angle of the seedling pot oriented support plate, and the height of the seedling pot significantly influence the posture of the strawberry seedling pot [4], these three factors were selected as experimental factors, with the deflection angle of the seedling pot after oriented planting as the evaluation index. As the seedling pot can fall smoothly when the opening and closing time of the seedling pot oriented support plate exceeds 0.5 s [4], to save planting time and improve efficiency, three data points (0.5, 0.6, and 0.7 s) were selected at equal intervals within the range of 0.5–0.7 s, corresponding to opening and closing speeds of 16.38°, 15.12°, and 13.86°/s, respectively. To ensure that the seedling pot oriented support plate does not interfere during opening and closing and that the seedling pot can fall smoothly from the support plate, an opening and closing angle greater than 9° ensures smooth dropping of the seedling pot [4], while an angle less than 12.6° avoids interference with the planter. Therefore, three data points were selected at equal intervals within the range of 9° to 12.6° for analysis. The height of the strawberry seedling pot affects its mass and center of gravity, which in turn influences the agronomic requirements of oriented planting during the transplanting process. The height of the strawberry seedling pot, ranging from 70 to 90 mm, has a significant impact on the posture of the seedling pot [4]. Thus, three data points were selected at equal intervals within the range of 70–90 mm for analysis. After analyzing the degree of influence of multiple factors, the optimal opening and closing speed, opening and closing angle of the seedling pot oriented support plate, and seedling pot height were selected to facilitate oriented planting in the strawberry transplanter [5].

To comprehensively investigate the relationship among the seedling pot height, the opening and closing speed of the seedling pot oriented support plate, the opening and closing angle, and the deflection angle of the strawberry seedling pot in this strawberry transplanter, the response surface Box-Behnken experimental design method was adopted. A three-factor, three-level orthogonal rotational combination experiment was designed using Design-Expert software. The experimental factor level coding table is shown in Table 1.

Table 1. Multifactor test level coding table

Variable	Experimental Factor	Low Level	Medium Level	High Level
A	Seedling pot height (mm)	70	80	90
B	Opening and closing speed (°/s)	13.86	15.12	16.38
C	Opening and closing angle (°)	9	10.8	12.6

A red calibration point A was established at the center of the square on the upper surface of the strawberry seedling pot, and a blue calibration origin O was established at one corner of the upper surface. The deflection angle was calculated by analyzing the vector coordinate variables of the blue and red calibration points. The original vector coordinate was $\overrightarrow{OA} = (x_1, y_1)$, and the vector coordinate after the deflection of the seedling pot was $\overrightarrow{O_1A_1} = (x_2, y_2)$. The coordinate transformation diagram for the deflection of the seedling pot is shown in Figure 3. The formula for calculating the deflection angle is:

$$\Delta\theta = |\theta - \theta_1| = |\frac{\pi}{2} - tan^{-1}(\frac{y2}{x2})| \quad (1)$$

Where:

$\Delta\theta$ — Deflection angle of the strawberry seedling pot, rad;

θ — Initial vector angle, rad;

θ_1 — Final vector angle, rad.

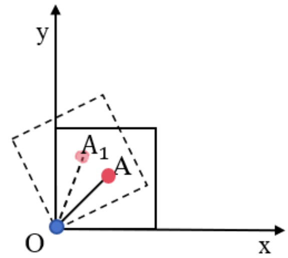


Figure 3. Deflection coordinate diagram of strawberry seedling bowl

The results of the response surface Box-Behnken experiment conducted using Design-Expert software were analyzed using the Analysis module of Design-Expert. A regression model was established, including the linear terms, quadratic terms, and first-order interaction terms between any two factors for seedling pot height, opening and closing speed of the seedling pot oriented support plate, and opening and closing angle. The regression equation is shown in Equation (2).

$$X = 176.89 - 0.46A - 146.47B - 4117.54C - 0.0125AB - 1.81AC - 37BC + 0.0034A^2 + 155.77B^2 + 36017C^2 \quad (2)$$

Table 2 presents the results of the regression equation analysis for the response value, the deflection angle of the strawberry seedling pot. The results indicate that the model for the deflection angle of the strawberry seedling pot is highly significant ($P < 0.01$). For the deflection angle experiment, the P-values for seedling pot height and the opening and closing angle of the seedling pot oriented support plate are less than 0.05, demonstrating that these factors have a significant impact on the response variable. From the analysis of multi-factor interaction levels, the order of influence is AC > BC > AB.

Table 2. Analysis of variance of the regression model of deflection angle of strawberry seedling bowl

Source of Variance	Sum of Squares	Degrees of Freedom	Mean Square	F-Value	P-Value
Model	6.4818	9	0.7202	9.9229	0.0031
A - Seedling pot height	0.4177	1	0.4177	5.7550	0.0475
B - Opening and closing speed	0.3461	1	0.3461	4.7687	0.0653
C - Opening and closing angle	0.7393	1	0.7393	10.1865	0.0152
AB	0.0002	1	0.0002	0.0022	0.9643
AC	0.0326	1	0.0326	0.4489	0.5243
BC	0.0003	1	0.0003	0.0047	0.9472
A^2	0.4937	1	0.4937	6.8023	0.0350
B^2	0.6385	1	0.6385	8.7977	0.0209
C^2	3.4137	1	3.4137	47.0348	0.0002

Based on the Box-Behnken experimental design principle within the response surface methodology, this study established a simulation experimental system with a three-factor, three-level parameter combination. The simulation results under various factor combinations were systematically analyzed using Design-Expert software. By employing the numerical optimization function in the software, multi-objective optimization was performed with the minimization of the strawberry seedling pot deflection angle as the optimization target. Through calculation and scheme screening, multiple sets of parameter combination optimization schemes that met the constraint conditions were obtained. Among these, the optimal parameter combination was determined as follows: seedling pot height of 80 mm, opening and closing speed of the seedling pot oriented support plate of 14.21°/s, and opening and closing angle of 10.60°. Under these conditions, the deflection angle of the strawberry seedling pot was 0.31°.

4. Field Experiment Verification

To validate the operational performance of the oriented planting device optimized through simulation for the electric strawberry seedling pot transplanter, field transplanting experiments were conducted for strawberry seedling pots under operating conditions with a plant spacing of 150 mm and varying ridge heights (300, 350, and 400 mm). The experiment site was selected as the Beijing experimental field, as shown in Figure 4. The strawberry seedling pots used were cultivated for approximately 8 weeks, with an average height ranging from 60 to 80 mm, and the planting depth was set to 70 mm. According to industry standards, the planting performance of the oriented planting device of the electric strawberry transplanter was evaluated to determine whether it meets the relevant indicators [6] and the agronomic requirements of strawberry seedling pots [2].

Figure 4. Beijing Experimental Field

Given the absence of clear evaluation standards specifically for the performance of strawberry transplanters, this study referred to the national standard "Dry Land Transplanting Machinery" (JB/T10291-2013) [7]. A total of 100 strawberry seedling pots were selected, and multiple experiments were conducted under three ridge heights of 300, 350, and 400 mm. The length of non-seedling mulching holes was tested to analyze the hole-forming performance of the transplanter. Additionally, an electronic protractor was used to measure the arch back deflection angle [8], as shown in Figure 5. The experimental results are presented in Tables 3 and 4.

(a) Planting effect diagram (b) Orientation measurement (c) Hole measurement

Figure 5. Inspection Diagram of Hole-forming Effects for Directional Planting

Table 3. Acupoint length test results

No.	Ridge height (mm)	Average hole length per group (mm)
1	300	134.5
2	350	137.4
3	400	145.3

Table 4. Test results of deflection angle of directional transplanting of strawberry seedlings

No.	Ridge height (mm)	Plant spacing (mm)	Experimental group (Deflection angle/°)						
			1	2	3	4	5	6	7
1	300	150	12.83	4.22	8.16	9.42	7.76	8.10	7.15
2	350	150	5.94	7.36	5.63	6.47	5.38	4.72	10.84
3	400	150	2.04	1.58	1.55	11.58	4.84	2.68	5.27

Analysis of the table shows that the average hole length was 139.1 mm, which remained within the qualified range and reduced the hole size. The overall transplanting performance met the national standard "Dry Land Transplanting Machinery" (JB/T10291-2013) and the agronomic requirements of strawberry seedling pots [2].

5. Conclusions

(1) Based on the agronomic requirements of strawberry seedling pots, an oriented planting device was designed. The device consists of a deep-planting mechanism driven by a servo motor through a screw transmission and a cam-type oscillating oriented clamping and seedling release mechanism, forming an integrated "orientation-seedling delivery-planting" operation system. This design meets the agronomic requirements of small strawberry plants with deep planting depths and significantly improves the automation level of transplanting operations.

(2) Based on the Box-Behnken experimental design, with the deflection angle of the strawberry seedling pot as the response variable, the optimal parameters were determined as follows: seedling pot height of 80 mm, opening and closing speed of the seedling pot oriented support plate of 0.248°/s, and opening and closing angle of 0.185°.

(3) Field experiments verified that the optimized oriented planting device, when integrated with the whole machine for operation, achieved an average hole length of 139.1 mm, which remained within the qualified range and reduced the hole size. This effectively addressed the challenges of deep planting depth, large hole size, and oriented transplanting of strawberry seedling pots.

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