Design and optimization of the seedling needle and push device for a mechanical transplanter of seedlings from bowl-type trays made of paddy straw

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Abstract: To meet the operational criteria for mechanical transplanting of young seedlings in paddy-straw-made bowl-seedling trays, a new seedling needle and seedling pushing device have been developed. This paper presents the design process and analyzes the effects of key parameters, including the angle of inclination of flat edge, width of flat edge, length of flat edge, wedge angle, and width of seedling pushing device for new seedling needle and seedling pushing device. Optimization parameters of new seedling needle and seedling pushing device have been validated by orthogonal experiments. The optimized values, such as a flat edge inclination angle of 35°, a flat edge width of 10 mm, a flat edge length of 64 mm, a wedge angle of 60°, and a seedling-pushing device width of 8 mm, satisfy the operational requirements for mechanically transplanting young seedlings in paddy-straw-made bowl seedling trays. The results demonstrate significant improvements in transplanting efficiency within Chinese agricultural systems.

Keywords: paddy-straw-made bowl-seedling trays, mechanical transplanting work, seedling needle, seedling pushing device, optimization
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1 Introduction

Enhancing the operational efficiency and yield of rice, a crucial agricultural crop in China, is of paramount importance for ensuring national food security. The mechanized cultivation technology for rice bowl-seedlings, a novel approach aligned with Chinese agricultural practices, has demonstrated consistent yield improvements through multi-year field validations[1]. Currently, Japan's pot seedling cultivation technology holds a leading international position. Its core research focuses on plastic seedling trays, which have been shown to significantly increase yields. However, the associated equipment remains costly. To reduce cultivation expenses, a novel carrier for rice pot seedling cultivation has been proposed. This method utilizes straw-processed bowl-shaped seedling trays as the cultivation medium[2-4], integrating automated substrate placement, precision seeding, and soil layering in a single operation. Seedlings cultivated in greenhouses for 40-45 d exhibit robust tillering[5-7]. The seedlings along with their bowl-shaped trays are transported to the field during transplantation. Therefore, a specialized mechanical device is required to precisely separate the seedlings along with its bowl-shaped trays from the nursery tray and transplant them into the paddy field with minimal root disturbance. However, field trials have demonstrated that conventional needle-push mechanisms are unsuitable for transplanting bowl-seedlings, necessitating the development of new devices.

A number of domestic and international institutions, including Japan's Yangma Agricultural Machinery Co., Ltd., Toyo Transplanter Co., Ltd., and Kubota Corporation, have developed specialized needles and push-roller devices for rice blanket seedlings, which have demonstrated satisfactory operational performance[8]. Xu et al.[9,10] conducted systematic research on transplanter mechanisms and orderly seedling feeding. While the above method demonstrates potential, it requires substantial refinement to enhance its practical applicability. Future research should focus on optimizing key parameters and validating the approach under more diverse conditions.

To address these technical bottlenecks, this study introduces a structurally optimized needle-push mechanism, specifically engineered for handling bowl-type seedling trays fabricated from rice straw. Through rigorous structural design and parameter optimization, the developed mechanism achieves reliable operation and meets the precision requirements of mechanized rice transplanting. These developments are instrumental in enhancing the technological maturity of automated seedling transplantation in China.

2 Design philosophy of seedling needle and push device

2.1 Structure of plant-fiber nursery trays

The rice planting tray object is shown in Figure 1. It has a

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length of 495 mm, a width of 277 mm, and a thickness of 23 mm. The tray features a grid pattern of 18 transverse and 7 longitudinal holes. Each hole has a square cross-section with a side length of 12.5 mm and a depth of 20 mm. Additionally, the bottom of the tray contains two rows of round holes, each with a diameter of 2 mm. These longitudinal round feed holes are spaced 50 mm apart to enable orderly longitudinal transplanting.

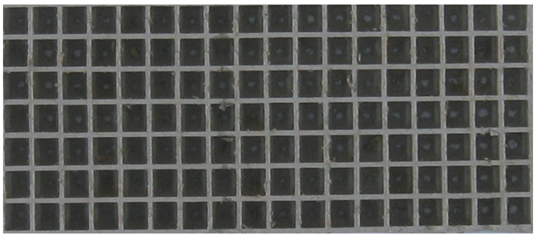
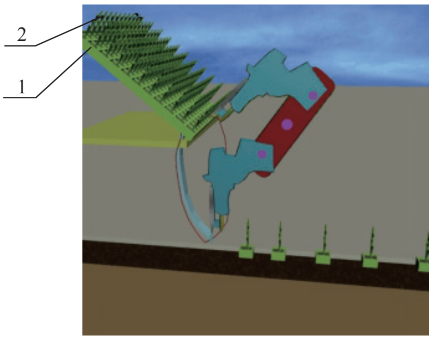


Figure 1 Bowl-growing tray for rice seedlings with substrate

2.2 Transplanting requirements

The straw-processed bowl-shaped seedling trays body is transplanted along with the pot seedling into the field. Compared with the existing transplanting technologies, the proposed method is not only more cost-effective but also enables the seedlings to develop within the pot under conditions that closely mimic the field environment, thereby eliminating the need for a recovery period after transplantation. The transplanting operation of rice pot seedlings is illustrated in Figure 2. During the transplanting process, the indexing mechanism of the transplanter separates and conveys seedlings from the tray sequentially to the picking position through intermittent motion. The seedling extraction device then applies external force to detach the entire pot seedling, along with its nursery tray hole, from the tray and accurately places it into the seed furrow.



1. Plant alms bowl 2. Plant pot seedling

Figure 2 Transplanting work

To ensure successful transplantation, the following requirements are specified. Seedlings are to be planted using a close, shallow method with a spacing of 10 cm and a depth of less than 20 mm to mitigate the impact of low temperature and enhance yield. Additionally, the rates of damaged and drifting seedlings should be below 2.5%, while the rate of intact potholes must exceed 90%.

2.3 Limitations of traditional seedling needle and push device

Seedling needles and seedling pushing devices are key components of transplanting machinery. The traditional types primarily comprise the PF455S and 2ZT4216A5 models, as shown in Figures 3 and 4, respectively. These two seedling needles are typically used in conjunction with the push device, illustrated in Figure 5.

The PF455S seedling needle, commonly referred to as the double-needle or 'U' type[11,12], is fabricated from alloy spring steel. With a body width of 12.5±0.2 mm and a length of 66 mm, it is specifically designed for the mechanized transplanting of blanket seedlings[13-15]. The supporting seedling pushing device is illustrated in Figure 5. However, when applied to the transplanting of seedlings in bowl-type trays made of paddy straw, this needle-pusher system exhibits several limitations: 1) The width of the needle body is small, causing two needles to act on the longitudinal adjacent side walls of the seedling bowl during cutting. This usually results in incomplete tearing of the side walls, with only part of the side wall being torn off. Additionally, the seedling needle lacks direct lateral action in seedling bowl, exerting only a longitudinal tearing effect. This significantly reduces the lateral integrity of plant potholes, which contradicts the requirements for plant pot seedling transplantation. 2) Given that the seedling tray is pressed with straw, its intensity is higher than that of blanket seedling soil. As a result, the seedling needle is prone to wear. 3) The PF455S seedling needle is used in combination with the seedling pushing device (see Figure 5). Due to the small opening of the seedling pushing device, the rates of damaged seedlings and floating seedlings increase, reaching maximum values of 5.31% and 6.24%, respectively.

Figure 3 PF455S seedling needle

Figure 4 2ZT4216A5 seedling needle

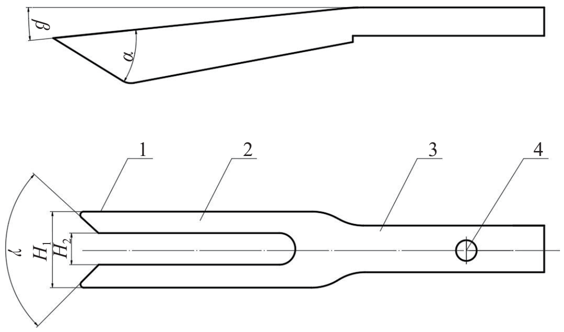
Figure 5 Seedling pushing device

The 2ZT4216A5 is a widely used seedling needle in mechanical transplanting. Compared to the PF455S seedling needle, the 2ZT4216A5 can tear the whole tray hole including young seedlings more effectively. However, when used in combination with the push device (see Figure 5), the rates of damaged seedlings and floating seedlings increase, reaching maximum values of 6.7% and 7.8%, respectively.

3 Structure design and working principle

3.1 Structural design

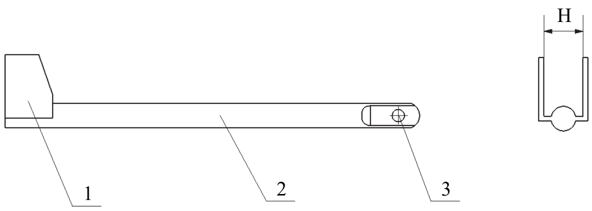
To address the limitations of traditional seedling needles and pushing devices in transplanting pot seedlings, a new type of seedling needle (see Figures 6 and 7) and a seedling pushing device (see Figure 8) have been developed. Their design is based on the principle of ensuring longitudinal feed, which is crucial for meeting the precision requirements of mechanized rice cultivation. The installation of the new seedling needle and pushing device is illustrated in Figure 9.



1. Cutting edge 2. Needle 3. Needle handle 4. Mounting hole

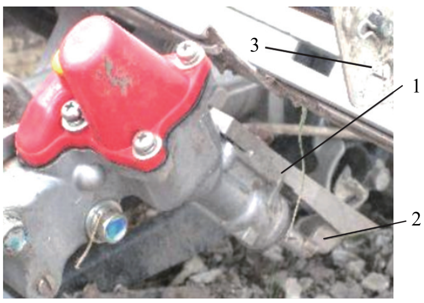
Figure 6 Diagram of new seedling needle

Figure 7 Physical image of new seedling needle



1. Pushing seedling block 2. Pushing seedling body 3. Mounting hole

Figure 8 New seedling pushing device



1. New seedling needle 2. New pushing seedling device 3. Planting aim

Figure 9 Assembly with new seedling needle and seedling pushing device

3.2 Main technical parameters

The operation procedure of the new seedling needle and pushing device is the same as that of the original transplanter. Driven by the transplanter's planting arm, the cutting edges on both sides of the new seedling needle cooperate with those at the front of the bowl to fully detach the seedling bowl. The potted seedling is then transferred and inserted into the shallow mud in the field[16-18]. The seedling bowl is then released from the needle via the pushing device. The wedge-shaped structure at the bottom of the new pushing device pushes the plant pot seedling block, ensuring that the seedlings are straightened in the field. This completes a single transplanting cycle.

To satisfy the agronomic requirements of straw-processed bowl-shaped seedling trays, the main technical parameters of the new seedling needle and pushing device are presented in Table 1.

Table 1 Main technical parameters of new seedling needle and pushing device

Design parameter	Value
Angle of the needle body β/(°)	5
Cutting edge plane angle γ/(°)	90
Thickness of side wall of seedling block/mm	2
Handle length/mm	45
Productivity/$hm^2 \cdot h^{-1}$	0.27-0.60

4 Design of key working parts

The key design parameters of the new seedling needle and pushing device include the body angle of the needle, the cutting edges, and the opening width of the push device. These parameters directly determine the performance of the transplanting operation.

4.1 Body angle of the needle

During the transplanting operation, the new seedling needle exhibits a compound motion: one driven by the planting arm, and the other following the transplanter's forward movement. To reduce the mechanical force on the seedling bowl and minimize damage, the needle should approach it at an oblique angle rather than vertically[19]. Extensive testing has demonstrated that a 5° downward tilt of the needle body (relative to the handle) minimizes resistance and bowl damage.

4.2 Cutting edge

The seedling pots, each with a central hole (or cell), are transported to the field along with the seedlings. To ensure high-quality transplanting and the complete separation of the pot from the seedling tray, the new seedling needle is designed to cut the tray matrix both horizontally and vertically. To achieve this, cutting edges are incorporated into both side walls and the needlepoint of the new seedling needle. Experiments demonstrated that the angle between the cutting edge and the side wall, along with the dimensions (width and length) of the cutting edge openings, significantly influence the transplanting performance. The specific effects of these parameters and their optimized values are discussed in the following section.

4.3 Opening width of the push device

Potted seedlings differ from conventional ones in two primary aspects: their greater robustness and the presence of tillers at transplantation, and their large root mass, which can cause the transplanter to tilt counteractively during operation, thereby increasing the rate of floating seedlings. To address these issues, a new pushing device has been designed, which incorporates the following key modifications compared to the conventional design. The first modification involves enlarging the opening width of the push block to mitigate seedling clamping and injury within the pot. The second modification features a wedge-shaped profile machined into the inner bottom of the push block. The height of this wedge increases progressively from the bottom to the top of the block. The angle between the wedge surface and the bottom plane of the push block is called the wedge angle.

The working principle of the wedge-shaped part is as follows. Since the planting bowl seedlings tend to tilt opposite to the transplanter, the push block moves downward with the transplanter. The wedge shape creates a height difference at the inner bottom of the push block, and the higher part lifts the tilted planting bowl seedlings as it moves downward, thereby reducing the floating seedling rate.

5 Field experiment

The field experiment was conducted at the Yunshan Farm Test Base of the Heilongjiang Agricultural Reclamation Administration from May 17 to 25, 2023.

5.1 Test methods

Five survey areas were selected using the diagonal sampling method, with each area located more than one working width away from the field edge. Along two diagonals in the survey area, measurements were taken for the distance from the mud surface to the water surface and the depth of the mud foot at each point. In each of the five test areas, the number of damaged seedlings and floating seedlings per hole were recorded.

5.2 Assessment indices

According to the agronomic requirements of rice transplanting, the evaluation index is the effect of mechanical transplanting operation, which includes the quality of machine transplanting (QOMT) and the quality of pothole cutting (QOPC).

Based on the agronomic requirements for rice pot seedling transplanting, the performance of mechanical transplanting is primarily evaluated in terms of its quality. The key metrics for assessing this quality are the seedling injury rate and the floating seedling rate.

5.2.1 Seedling injury rates

The damaged seedling rate is defined as:

$$R_s = \frac{Z_s}{Z} \times 100\% \qquad (1)$$

where, R_s is the rate of damaged seedling, Z_s is the number of damaged seedlings, and Z is the determination of total plant number.

5.2.2 Floating seedling rate

The floating seedling rate is calculated as follows:

$$R_p = \frac{Z_p}{Z} \times 100\% \qquad (2)$$

where, R_p is the rate of floating seedling, Z_p is the number of floating seedlings, and Z is the determination of total plant number.

5.2.3 Quality of pothole cutting

The cutting quality of the bowl hole is characterized by its integrity. Bowl hole integrity refers to the condition of the bowl after transplanting in the field under the action of the new seedling needle and the seedling pusher. It is determined by the following equation:

$$K = \frac{K_1}{126} \times 100\% \qquad (3)$$

where, K is the bowl hole integrity rate, and K_1 is the number of intact bowl holes. (Note: The actual pothole depth exceeds 50% of the theoretical value (20 mm). The seedling tray used has 126 cells.)

5.3 The various factors affecting the machine insertion operation

5.3.1 Angle of cutting edge

The influence of the angle of cutting edge (θ, °) on mechanical transplanting operation was tested under the following conditions. The new seedling needle cutting edge opening width is 8 mm, the needle body has an opening length of 62 mm, the wedge angle of the pushing seedling block is 60°, and the opening width of pushing seedling block is 8 mm. The test results are shown in Figure 10.

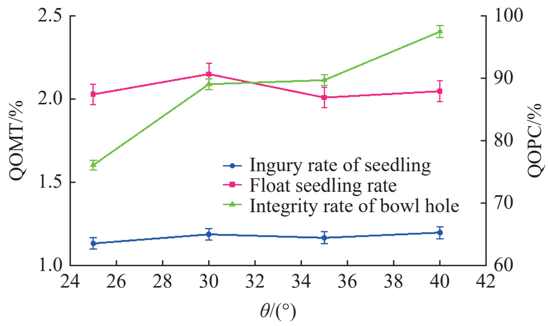


Figure 10 Different angle of inclination of flat edge influence on mechanical transplanting work

Figure 10 illustrates the influence of the cutting edge angle of the new seedling needle on the damaged and floating seedling rates. As shown, both rates exhibit limited sensitivity to increases in the cutting edge angle. This observed insensitivity can be attributed to the efficient cutting action of the needle's blade. Across the tested range of angles, the blade consistently shears the planting bowl cleanly, thereby minimizing root disruption and subsequent seedling damage or flotation.

The influence of the cutting edge angle on the pothole integrity is also shown in Figure 10. The pothole integrity increases with the cutting-edge angle. This is mainly due to the increased effective cutting-edge length on the pothole side wall, which ensures complete cutting and thus improves the pothole integrity rate.

5.3.2 Opening width of cutting edge

The influence of the cutting-edge opening width (w_1, mm) on machine transplanting operation was tested under the following conditions: a new seedling needle cutting edge inclination angle of 35°, needle opening length of 62 mm, wedge angle of the pushing seedling block of 60°, and opening width of the pushing seedling block of 8 mm. The test results are shown in Figure 11.

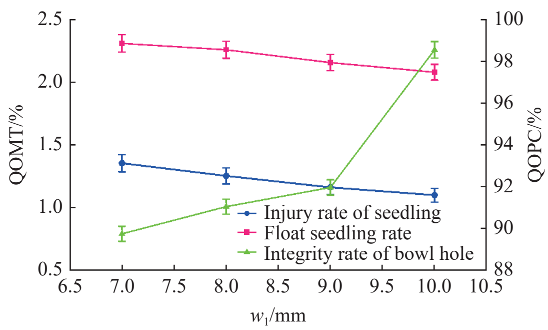


Figure 11 Different width of flat edge influence on mechanical transplanting work

The influence of the cutting edge opening width of the new seedling needle on the damaged seedling rate and floating seedling rate is shown in Figure 11. Both rates decrease as the cutting edge opening width increases. This is mainly because a wider cutting edge opening reduces the probability of damaging the plant pot seedlings, thereby lowering the damaged and floating seedling rates.

The influence of the cutting-edge opening width on the pothole integrity is also shown in Figure 11. The pothole's integrity increases with the cutting edge opening width. This is primarily due to the increased area of the bowl hole side wall subjected to the cutter's force, which is more uniformly distributed. This weakens the mutual pulling effect of the bowl hole, thus improving its integrity.

5.3.3 Opening length of needle body

The influence of the opening length of needle body (L, mm) on machine transplanting was tested under the following conditions: a new seedling needle cutting edge angle of 35°, cutting edge opening width of 8 mm, wedge angle of pusher of 60°, and opening width of pusher of 8 mm. The test results are shown in Figure 12.

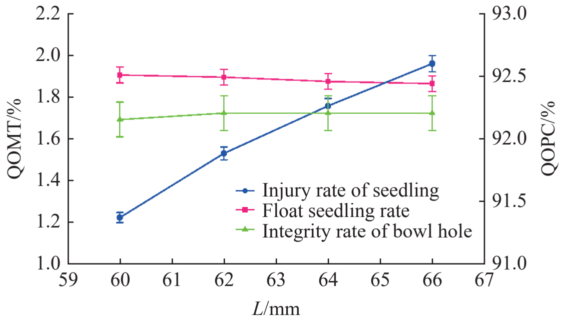


Figure 12 Different length of flat edge influence on mechanical transplanting work

The influence of the opening length of the new needle on the damaged seedling rate and floating seedling rate is shown in Figure 12. The damaged seedling rate remains unchanged as the needle opening length increases, while the floating seedling rate increases significantly. This phenomenon can be attributed to the well-developed nature and tillering of the seedlings. A longer opening length prolongs the retention time within the needle. Consequently, the seedlings and their tillers become crowded inside the needle cavity. This crowding leads to incomplete or unstable placement into the soil, ultimately causing the seedlings to be pulled out or to float in the mud layer.

The influence of the needle body opening length on pothole integrity is presented in Figure 12. The pothole's integrity remains unchanged with the increase in needle body opening length. This is because the bowl hole cutting is primarily influenced by the cutting edge, and the needle body opening length has little effect on it.

5.3.4 Wedge angle of pushing seedling block

Under the conditions of a new seedling needle cutting edge angle of 35°, cutting edge opening width of 8 mm, needle body opening length of 62 mm, and pushing seedling block opening width of 8 mm, the influence of the wedge angle of pushing seedling block (ϕ, °) on machine transplanting operation was tested. The test results are shown in Figure 13.

The influence of the wedge angle on the damaged seedling rate and floating seedling rate is shown in Figure 13. Both rates decrease as the wedge angle increases. This is mainly because, on one hand, a larger wedge angle reduces the probability of seedling clamping. On the other hand, the increased height difference between the upper and lower parts of the push block's inner bottom improves seedling cultivation, thereby reducing the damaged and floating seedling rate.

As shown in Figure 13, the influence of the wedge angle on the bowl hole integrity remains unchanged with the increase in wedge angle. This is because the bowl hole is primarily affected by the cutting edge of the new seedling needle, and the wedge angle of the pushing seedling block has minimal influence on it.

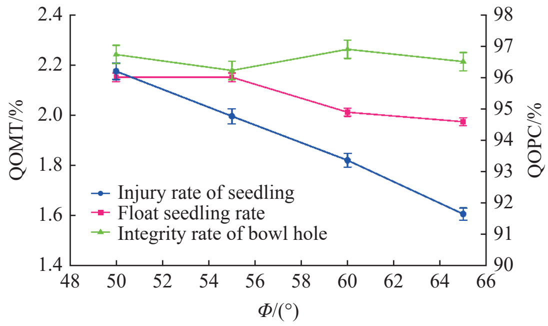


Figure 13 Different wedge angle influence on mechanical transplanting work

5.3.5 Opening width of seedling pushing device

To evaluate the influence of the push device's opening width (w_2, mm) on transplanting performance, tests were conducted with the following fixed parameters: a cutting edge angle of 35°, a cutting edge opening width of 8 mm, a needle body opening length of 62 mm, and a pushing block wedge angle of 60°. The results are presented in Figure 14.

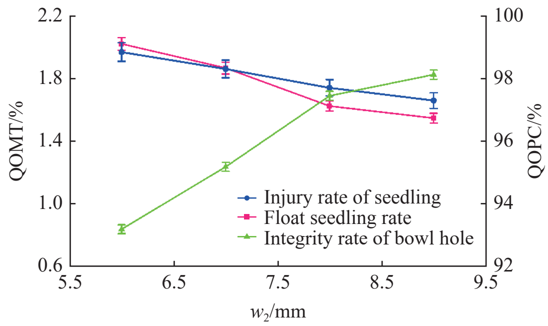


Figure 14 Different width of seedling pushing device influence on mechanical transplanting work

The influence of the opening width of the pushing device on the damaged seedling rate and bleached seedling rate is shown in Figure 14. As the opening width increases, both the damaged seedling rate and bleached seedling rate decrease. This is primarily because a larger opening width reduces the clamping and blocking of seedlings in the pushing device, thereby decreasing the damaged and floating seedling rates.

The effect of the seedling pusher's opening width on pothole integrity is presented in Figure 14. The integrity improves as the opening width increases. This improvement is primarily because a greater distance between the pusher sidewalls and the pothole wall distributes the applied force over a larger area. Consequently, the stress concentration on the pothole wall is reduced, resulting in less damage.

5.4 Parameter optimization

The damaged seedling rate, floating seedling rate, and intact pothole rate are key indices of mechanical transplanting performance for plant pot seedlings. On the one hand, lower damaged and floating seedling rates indicate better transplanting effectiveness, while higher pothole integrity also reflects improved performance. On the other hand, the optimal parameter combination for minimizing damaged seedling rate may not necessarily optimize the bleaching seedling rate and bowl hole integrity rate.

The experimental results for each index were comprehensively analyzed using the comprehensive balance analysis method to determine the optimal solution. Specifically, range analysis and analysis of variance were used to determine the significance and degree of influence of influencing factors on the rate of damaged seedlings, the rate of floating seedlings, and the rate of pothole integrity. Subsequently, the trends of these three performance indices in response to the factor levels were examined.

An $L_{16}(4^5)$ orthogonal table was used for the experiment, with each trial repeated three times. There were 100 seedlings taken in the measurement. The factors and their corresponding levels are presented in Table 2.

Table 2 Factors and levels of orthogonal experiments

Levels	Experimental Factors				
	A	*B*	*C*	*D*	*E*
1	25	7	60	50	6
2	30	8	62	55	7
3	35	9	64	60	8
4	40	10	66	65	9

Note: *A*: Cutting edge inclination angle; *B*: Cutting edge opening width; *C*: Needle body opening length; *D*: Pushing block wedge angle; *E*: Pushing device opening width. The same as below.

The test results are presented in Table 3, with the variance and range analysis as listed in Tables 4 and 5, respectively.

Using the seedling injury rate as the evaluation index, the variance analysis (see Table 4) reveals that, under the given conditions, the opening length of the needle body and the wedge angle of the pushing block have significant effects on the seedling injury rate, while the inclination angle of the cutting edge, the opening width of the cutting edge, and the opening width of the pushing device also exhibit significant effects. According to the range analysis of the damaged seedling rate results (see Table 5), the order of priority of the factors is *C*, *D*, *A*, *B*, and *E*. As a lower seedling injury rate is preferable, the optimal combination for minimizing the seedling injury rate is $C_3D_4A_3B_1E_3$.

Using the floating seedling rate as the evaluation index, the variance analysis (see Table 5) indicates that the opening length of the needle body and the wedge angle of the pushing block have extremely significant effects on the floating seedling rate, the opening width of the cutting edge has a significant effect, while the inclination angle of the cutting edge and the opening width of the

Table 3 Results of orthogonal experiments

Test No.	*A*	*B*	*C*	*D*	*E*	Seedling injury rates/%	Floating seedling rate/%	Bowl hole integrity rate/%
1	1	1	1	1	1	2.18	1.48	50.76
2	1	2	2	2	2	2.06	1.57	84.61
3	1	3	3	3	3	1.95	1.34	93.92
4	1	4	4	4	4	1.88	2.31	80.02
5	2	1	2	3	4	1.88	1.57	90.38
6	2	2	1	4	3	1.93	2.14	73.90
7	2	3	4	1	2	1.96	1.99	82.21
8	2	4	3	2	1	1.79	1.81	95.45
9	3	1	3	4	2	1.11	2.17	66.91
10	3	2	4	3	1	1.94	2.06	81.38
11	3	3	1	2	4	2.12	1.62	75.21
12	3	4	2	1	3	1.94	1.93	95.04
13	4	1	4	2	3	1.96	1.89	86.99
14	4	2	3	1	4	1.99	1.62	90.82
15	4	3	2	4	1	2.05	1.79	77.30
16	4	4	1	3	2	1.93	1.92	82.63

Table 4 Analysis of variance

Assessment indices	Factor	Sum of squares	DoF	Mean square	*F*	Significance
Seedling injury rate	*A*	0.403	3	0.134	4.397	*
	B	0.408	3	0.136	4.453	*
	C	0.748	3	0.249	8.615	*
	D	0.536	3	0.179	5.857	*
	E	0.381	3	0.127	4.159	*
	Error	0.977	32	0.031		
	Total	3.453	47			
Floating seedling sate	*A*	0.471	3	0.157	2.445	
	B	0.607	3	0.202	3.151	*
	C	0.932	3	0.311	4.839	*
	D	1.239	3	0.413	6.430	*
	E	0.131	3	0.044	0.681	
	Error	2.055	32	0.064		
	Total	5.435	47			
Bowl hole integrity rate	*A*	862.346	3	287.449	3.064	*
	B	1320.579	3	440.190	4.692	*
	C	1861.259	3	620.419	6.613	*
	D	925.625	3	308.542	3.288	*
	E	622.012	3	207.337	2.210	
	Error	3002.406	32	93.825		
	Total	8594.227	47			

Table 5 Range analysis

Indices	Factors	Total				Mean value				Maximum	Minimum	Range
		K_1	K_2	K_3	K_4	k_1	k_3	k_3	k_4			
Seedling injury rate	*A*	8.07	7.56	7.11	7.93	2.02	1.89	1.78	1.98	2.02	1.78	0.24
	B	7.13	7.92	8.02	7.54	1.78	1.98	2.00	1.89	2.00	1.78	0.22
	C	8.16	7.93	6.84	7.74	2.04	1.98	1.71	1.94	2.04	1.71	0.33
	D	8.07	7.93	7.7	6.97	2.02	1.98	1.93	1.74	2.02	1.74	0.28
	E	7.96	7.89	7.78	7.87	1.99	1.97	1.95	1.97	1.99	1.95	0.04
Floating seedling rate	*A*	6.70	7.51	7.78	7.22	1.68	1.88	1.95	1.81	1.95	1.68	0.27
	B	7.11	7.39	6.74	7.97	1.78	1.85	1.69	1.99	1.99	1.69	0.36
	C	7.16	6.86	6.94	8.25	1.79	1.72	1.74	2.06	2.06	1.72	0.34
	D	7.02	6.89	6.45	8.41	1.76	1.72	1.61	2.10	2.10	1.61	0.49
	E	7.14	7.65	6.89	7.12	1.79	1.91	1.72	1.78	1.91	1.72	0.19
Bowl hole integrity rate	*A*	299.31	341.94	318.54	337.74	74.83	85.49	79.64	84.44	85.49	74.83	10.66
	B	295.04	318.64	318.64	353.14	73.76	79.66	79.66	88.29	88.29	73.76	14.53
	C	282.50	352.66	337.10	330.60	70.63	88.17	84.28	82.65	88.17	70.63	17.54
	D	318.83	342.26	338.31	298.13	79.71	85.57	84.58	74.53	85.57	74.53	11.04
	E	304.89	316.36	349.85	336.43	76.22	79.09	87.46	84.11	87.46	76.22	11.24

pushing device show no significant effects. According to the results of range analysis (see Table 5), the order of priority of the factors is *D*, *B*, *C*, *A*, and *E*. As a lower floating seedling rate is preferable, the range analysis of the floating seedling rate results (see Table 5) identifies the optimal combination as $D_3B_3C_2A_1E_3$.

Analysis of variance for bowl hole integrity is presented in Table 5. The results reveal that the opening width of the cutting edge (Factor *B*) and the opening length of the needle body (Factor *C*) significantly affect the integrity. The inclination angle of the cutting edge (Factor *D*) and the wedge angle of the pushing block (Factor *E*) also show significant effects. In contrast, the opening width of the pushing device (Factor *A*) demonstrates no significant effect. According to the results of range analysis (see Table 5), the order of priority of the factors is *C*, *E*, *B*, *D* and *A*. As a higher bowl hole integrity rate is preferable, the range analysis of the pothole integrity results (Table 5) determines the optimal combination to be $C_2B_4E_3D_2A_2$.

Factor *A* is a relatively dominant factor for the first index (damaged seedling rate), with A_3 being the optimal level; however, it is relatively less significant for the other two indices. Therefore, A_3 was selected based on the relative importance of Factor *A* across different indices. Factor *B* is relatively dominant for the second (floating seedling rate) and third (bowl hole integrity rate) indices, with B_3 and B_4 being the respective optimal levels. Further analysis of the trend diagrams of each index with respect to Factor *B* reveals that the overall optimal choice is B_4. Factor *C* is the most dominant factor for both the first and third indices, with C_3 and C_2 being the respective optimal levels. By further examining the trend diagrams of each index in relation to Factor *C*, it can be concluded that C_3 represents the overall optimal level. Factor *D* is the most significant factor for the second index, with D_3 being the optimal level, while it plays a relatively minor role in the other two indices. Thus, D_3 was selected. For all three indices, E_3 consistently represents the optimal level, and therefore E_3 was chosen.

Combined with the comprehensive value, the optimal parameter combination scheme is determined as $A_3B_4C_3D_3E_3$. The specific parameters of the optimal solution are as follows: the cutting edge angle was 35°, the cutting edge opening width was 10 mm, the needle body opening length was 64 mm, the pushing block wedge angle was 60°, and the seedling pushing device opening width was 8 mm. With this optimal combination, the performance metrics were as follows: a damaged seedling rate of 1.95%, a floating seedling rate of 1.34%, and a pothole integrity rate of 93.92%. These results meet the operational requirements for the mechanical transplanting of potted seedlings.

5.5 Experimental results

To verify the correctness of the optimized parameter combination, a validation test was conducted based on the optimal combination. The test results were as follows: the damaged seedling rate was (1.93±0.03)%, the floating seedling rate was (1.30±0.02)%, and the pothole integrity rate was (93.20±0.13)%. These results meet the requirements for mechanical transplanting of plant pot seedlings.

6 Conclusions

1) Based on the requirements for mechanical transplanting of plant pot seedlings, the corresponding seedling needle and seedling pushing device were designed. The influence of various factors on the mechanical transplanting performance was analyzed.

2) The structural optimization parameters for the new seedling needle and seedling pushing device were determined as follows: The cutting edge angle was 35°, the cutting edge opening width was 10 mm, the needle body opening length was 64 mm, the pushing block wedge angle was 60°, and the seedling pushing device opening width was 8 mm.

3) The optimized results were validated through field tests. The experimental results were as follows: The damaged seedling rate was (1.93±0.03)%, the bleaching seedling rate was (1.30±0.02)%, and the hole integrity rate was (93.2±0.13)%. These results demonstrate that the performance met the agronomic requirements for the mechanical transplanting of potted seedlings.

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