OPTIMIZATION AND TESTING OF OPERATING PARAMETERS FOR THE AUTOMATIC SEEDLING PICKING DEVICE OF TOMATO POT SEEDLING TRANSPLANTER

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番茄钵苗移栽机自动取苗装置作业参数优化与试验

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ABSTRACT

This study focused on an in-depth analysis of the cam motion process of the seedling clamp within the automatic seedling-picking device for tomato pot seedlings. Key influencing factors, including spring stiffness coefficient, seedling needle holding angle, and seedling-picking frequency, were selected for investigation. Evaluation indicators included substrate loss rate, pot seedling drop rate, and seedling-picking success rate. A three-factor, three-level, second-order rotational orthogonal combination test was conducted. Using Design-Expert V13.0.5 software for data analysis, the theoretical optimal parameter combination was identified: a spring stiffness coefficient of 376.8 N/m, a seedling needle holding angle of 15.6°, and a seedling-picking frequency of 89 plants per minute. Under this parameter combination, the substrate loss rate was reduced to 3.94%, the pot seedling drop rate to 2.01%, and the seedling-picking success rate reached 94.05%. A verification test conducted on the seedling-picking device test bench showed that the experimental results closely aligned with the optimized theoretical values. These findings provide a valuable reference for the structural optimization and performance improvement of seedling-picking devices in fully automatic tomato transplanters and contribute significantly to the advancement of automation in tomato transplanting operations.

摘要

本研究聚焦于番茄钵苗自动取苗装置中的夹苗器凸轮运动过程展开深入分析。在研究过程中，选定弹簧刚度系数、苗针夹持角度以及取苗频率作为关键影响因素，并将基质损失率、钵苗脱落率和取苗成功率确定为评价指标，进而开展三因素三水平二次旋转正交组合试验。借助 Design-Expert.V13.0.5 软件对试验数据进行分析处理，最终获取理论上的最优参数组合，即弹簧刚度系数为 376.8 N/m，苗针夹持角度为 15.6°，取苗频率为 89 株 /min。在该参数组合条件下，基质损失率低至 3.94%，钵苗脱落率仅为 2.01%，而取苗成功率高达 94.05%。随后，在取苗装置上进行验证试验，试验结果与优化所得理论结果基本相符。本研究所得的相关成果，能够为番茄全自动移栽机取苗装置的结构优化改进以及作业参数的精准控制提供有益的参考借鉴，对于推动番茄移栽作业的自动化发展具有重要意义。

INTRODUCTION

Ningxia serves as a pivotal production region for processing tomatoes in China. The tomato - related industry holds a place of considerable importance in Ningxia's agricultural production landscape *(Niu et al., 2022).* In recent years, Ningxia has predominantly employed seedling transplanting technology in tomato cultivation. With the continuous expansion of the planting scale, the annual demand for transplanting machinery during the spring season has also been on the rise *(Liu et al., 2013).* At present, the transplanting machinery in use is predominantly semi - automatic. The seedling-picking operation still needs to be completed manually, which is characterized by low automation, high labor intensity, low efficiency, and high operating costs.

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These factors are significantly hindering the advancement of seedling transplanting technology *(Yu et al., 2014; Zhang et al., 2013; Hu et al., 2014)*. Therefore, the automatic transplanting machine has become an inevitable development trend for achieving efficient and large-scale crop transplanting in Ningxia. It is imperative to advance the research and development of fully automatic transplanting machines equipped with automatic seedling-picking and seedling-dropping functions. The core of automatic transplanting machine research and development lies in automatic seedling picking technology. At present, both domestic and international research on mechanical automatic seedling-picking methods for automatic transplanting machines primarily focus on two approaches: the clamping (folder-picking) type and the ejecting type. Automatic transplanting machines developed using these two methods have already been applied in foreign countries *(Dixit., 2010; Manjunatha et al., 2009; Sakaue, 1996)*. Although this type of fully automatic transplanting machine offers high working efficiency and a high degree of automation, it is expensive, structurally complex, and primarily designed for bare-soil transplanting. As a result, it does not meet the agronomic requirements for transplanting on mulch film making it unsuitable for introduction and widespread adoption *(Huang et al., 2023)*. Domestic research on transplanting machinery started relatively late; however, several semi-automatic transplanting machine models have already been developed, applied, and promoted *(Xue et al., 2013; Jin., 2014)*. In recent years, several domestic universities and research institutes have conducted extensive research on automatic seedling extraction mechanisms, which are core components of automatic vegetable transplanters. Their work has focused on the mechanical properties of pot seedlings *(Chen et al., 2024; Hu et al., 2023)*, the structural design of seedling extraction claws *(Han et al., 2013; Liang et al., 2018; Han et al., 2015)*, the optimization and simulation analysis of key components in the seedling extraction mechanism *(Hai et al., 2025; Wang et al., 2015)*, and experimental studies on key parameters *(Gao et al., 2015; Zhang et al., 2016; Zhang, 2014)*. However, despite this progress, no mature technology has yet been successfully applied in actual agricultural production.

This paper focuses on a tomato pot seedling automatic extraction device developed by the research group. A seedling extraction test bench was established to support experimental analysis. The seedling extraction mechanism employs a planetary gear–linkage system combined with an irregular slide drive to control the clamping motion and achieve the desired trajectory and posture for automatic seedling extraction. A cam-toggle mechanism is used to control the opening and closing of the seedling clamping needles, enabling both clamping and seedling releasing actions. Using the test bench and applying response surface method, the study optimizes key operating parameters of the device to enhance operational quality. The findings aim to provide a reference for the structural optimization and design improvement of automatic seedling extraction devices.

MATERIALS AND METHODS

Structure and working principle of automatic seedling picking device

The seedling extraction device is the core component of the automatic seedling extraction test bench. It is primarily composed of a rackmount, planetary gearbox, connecting rod, seedling needle, seedling pushing ring, cam, slide, etc., as illustrated in Fig. 1.

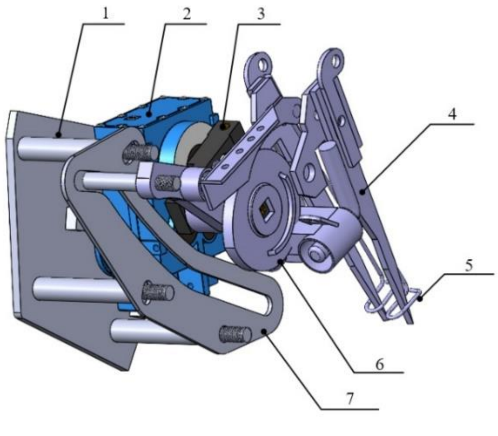


Fig. 1 – Overall system architecture Figure

Schematic diagram of tomato pot seedling automatic picking device

1.Rackmount; 2. Planetary gearbox; 3. Connecting rod; 4. Seedling needle; 5. Seedling pushing ring; 6. Cam; 7. Slide

According to the requirements of seedling picking and dropping operation *(Li et al., 2015; Ye et al., 2014)*, the cam's working stroke is divided into four working phases: preparation for seedling picking, seedling clamping, seedling holding and seedling releasing, as shown in Fig. 2. To prepare the seedling clamping section AB, the two seedling needles are fully opened, the push ring slides upward along the seedling needles under the action of the cam, and the seedling needles approach the holes at a fixed angle. In the seedling clamping section BD, the seedling needles were inserted into the holes at a fixed angle, and when they reached point C, the distance between the tip points of the two seedling needles was gradually reduced to clamp the root plug, and the distance between the tip points of the seedling needles remained unchanged after the root plug was clamped. In the seedling holding section DF, the seedling needles vertically pull the pot seedling out from the tray holes. During this stage, the seedling pushing ring remains stationary. As the mechanism moves along the cam profile to point F, the seedling holding stage ends and the seedling needles begin to open. At this point, the pot seedling assumes a vertically downward posture. In the seedling release section FA, as the mechanism progresses to stage GA, the seedling pushing ring slides downward along the seedling needles. When it reaches point A, the pushing ring completes its stroke, pushing the seedling vertically downward to release it. Simultaneously, the seedling needles open and return to their initial angle, completing one full cycle of seedling extraction and release.

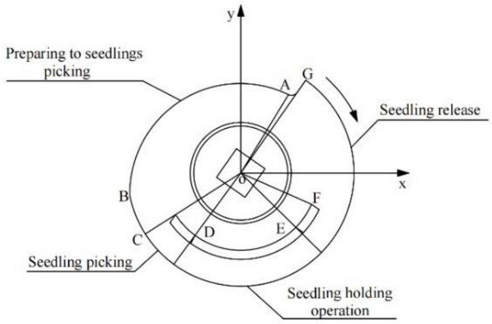


Fig. 2 – Cam working stroke

Principle of system operation

In order to investigate the effects of spring stiffness coefficient, clamping angle of seedling needle and seedling picking frequency on the performance of seedling picking device and the optimal combination of parameters, a three-factor and three-level quadratic rotary optimization experiment was carried out with the indicators of substrate loss, seedling shedding rate and seedling picking success rate. The spring stiffness coefficients X_1 were set at 300, 400 and 500 N/m, and the clamping angles X_2 were set at 14, 16 and 18°, respectively, the seedling picking frequency X_3 was set at 60, 90 and 120 plants/min. The quadratic rotary orthogonal combination scheme was designed, 20 groups of automatic seedling extraction device performance tests were conducted, each group of experiments was repeated three times and the average of the three test results was taken as the experimental results. Design-Expert.13.0.5 software was used to design the experimental scheme and analyze the results, as shown in Table 1.

Table 1

Experimental design and results

No.	X_1	X_2	X_3	Substrate loss rate Y_1/%	Pot seedling shedding rate Y_2/%	Success rate of seeding picking Y_3/%
1	**-1**	**-1**	**-1**	6.21	1.55	92.24
2	**1**	**-1**	**-1**	12.53	1.57	85.9
3	**-1**	**1**	**-1**	4.68	9.36	85.96
4	**1**	**1**	**-1**	6.94	5.49	87.57
5	**-1**	**-1**	**1**	10.21	5.48	84.31
6	**1**	**-1**	**1**	19.56	6.27	74.17
7	**-1**	**1**	**1**	5.48	9.41	85.11
8	**1**	**1**	**1**	12.52	7.83	79.65
9	**-1.682**	**0**	**0**	3.93	7.02	89.05
10	**1.682**	**0**	**0**	13.29	4.71	82
11	**0**	**-1.682**	**0**	14.07	2.35	83.58
12	**0**	**1.682**	**0**	5.43	9.37	85.2
13	**0**	**0**	**-1.682**	3.91	2.33	93.76
14	**0**	**0**	**1.682**	12.57	7.82	79.61
15	**0**	**0**	**0**	4.71	2.35	92.94
16	**0**	**0**	**0**	5.44	1.57	92.99

No.	X_1	X_2	X_3	Substrate loss rate Y_1/%	Pot seedling shedding rate Y_2/%	Success rate of seeding picking Y_3/%
17	**0**	**0**	**0**	4.68	2.36	92.96
18	**0**	**0**	**0**	3.94	2.37	93.69
19	**0**	**0**	**0**	4.01	1.59	94.4
20	**0**	**0**	**0**	4.76	2.31	92.93

Experimental results and analyses

Quadratic polynomial regression models were established between spring stiffness coefficient, clamping angle of seedling-picking needle, frequency of seedling picking and substrate loss rate, pot seedling shedding rate and seedling picking success rate. The regression equations were obtained by eliminating the insignificant factors.

$$Y_1 = 4.57 + 2.98X_1 - 2.45X_2 + 2.34X_3 - 0.80X_1X_2 + 0.98X_1X_3 - 0.58X_2X_3 + 1.56X_1^2 + 1.96X_2^2 + 1.43X_3^2 \tag{1}$$

$$Y_2 = 0.21 - 0.62X_1 + 2.13X_2 + 1.48X_3 - 0.78X_1X_2 + 0.38X_1X_3 - 0.78X_2X_3 + 1.35X_1^2 + 1.34X_2^2 + 1.07X_3^2 \tag{2}$$

$$Y_3 = 93.34 - 2.36X_1 + 0.32X_2 - 3.82X_3 + 1.58X_1X_2 - 1.36X_1X_3 + 1.36X_2X_3 - 2.90X_1^2 - 3.30X_2^2 - 2.49X_3^2 \tag{3}$$

The results showed that the regression equation models for substrate loss rate, pot seedling shedding rate, and seedling removal success rate were P < 0.0001, indicating that the three regression equation models were significant, suggesting that the regression models fitted well within the experimental range.

Table 2

Variance analysis of regression models

Indexes	Variance source	Sum of squares	Degree of freedom	Mean square	F value	P value
Y_1	**Model**	393.75	9	43.75	102.39	< 0.0001
	Residual	4.27	10	0.4273		
	Lack of Fit	2.74	5	0.5480	1.79	0.2697
	Pure Error	1.53	5	0.3066		
Y_2	**Model**	165.39	9	18.38	135.74	< 0.0001
	Residual	1.35	10	0.1354		
	Lack of Fit	0.5662	5	0.1132	0.7188	0.6370
	Pure Error	0.7877	5	0.1575		
Y_3	**Model**	635.07	9	70.56	100.16	
	Residual	7.05	10	0.7045		
	Lack of Fit	5.21	5	1.04	2.83	0.1389
	Pure Error	1.84	5	0.3677		

RESULTS

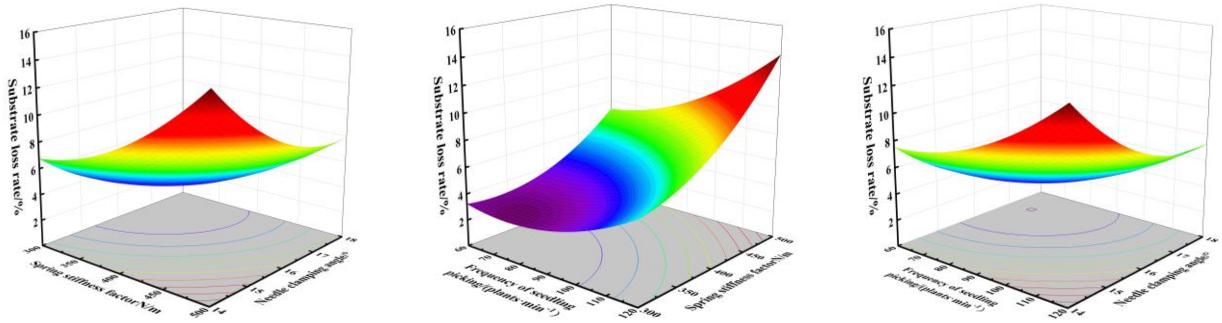
Effect of interaction factors on the substrate loss rate

The substrate loss rate's response surface is illustrated in Fig. 3. As shown in Fig. 3(a), when the seedling picking frequency is 90 plants/min, the substrate loss rate exhibits an upward trend with the increasing needle clamping angle, while it shows a downward trend with the rising spring stiffness coefficient. The response surface demonstrates a relatively rapid change in the direction of the needle clamping angle, whereas the change in the direction of the spring stiffness coefficient is relatively slow. At a certain seedling picking frequency, the impact of the needle clamping angle on the substrate loss rate is more pronounced than that of the spring stiffness coefficient. A lower substrate loss rate was observed at a spring stiffness coefficient of approximately 400 N/m and a needle clamping angle of around 16°.

As depicted in Fig. 3(b), when the clamping angle of the seedling needle is set at 16°, an increase in the spring stiffness coefficient leads to a higher rate of substrate loss. Similarly, as the frequency of seedling extraction rises, the rate of substrate loss also shows an upward trend.

The response surface analysis reveals that the substrate loss rate is more sensitive to changes in the spring stiffness coefficient, exhibiting a relatively rapid variation along this direction. In contrast, its change along the direction of seedling extraction frequency is comparatively slower.

As shown in Fig. 3(c), when the spring stiffness coefficient is fixed at 400 N/m, the substrate loss rate initially rises and then declines with increasing seedling extraction frequency, while it consistently increases with an increasing needle clamping angle. The response surface exhibits a more pronounced change in the direction of the needle clamping angle compared to the direction of the seedling extraction frequency. This indicates that, for a given spring stiffness coefficient, the needle clamping angle has a more significant impact on the substrate loss rate than the seedling extraction frequency.



(a) (b) (c)

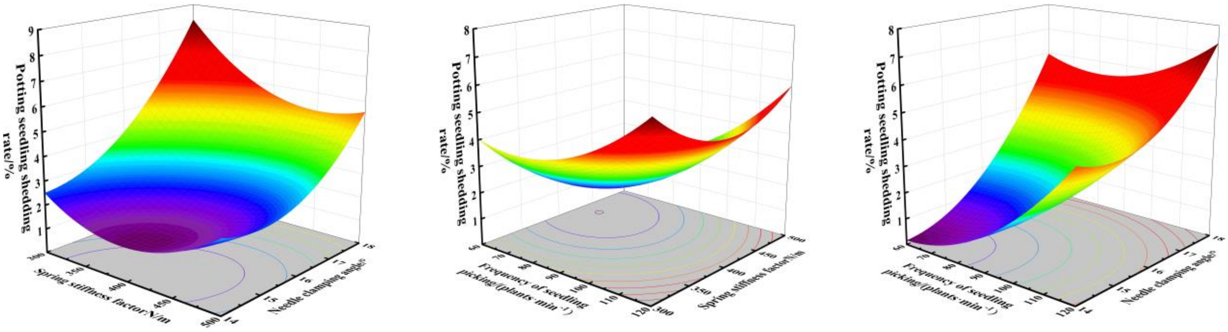
Fig. 3 – Effect of interaction factors on substrate loss rate

Effect of interaction factors on the pot seedling shedding rate

The response surface of the seedling shedding rate is presented in Fig. 4. As depicted in Fig. 4(a), when the seedling picking frequency is 90 plants/min, the seedling shedding rate increases with the increasing seedling needle clamping angle and first decreases and then increases with the rising spring stiffness coefficient. The response surface analysis indicates that the seedling shedding rate changes along the direction of the spring stiffness coefficient, but the rate of change is faster along the direction of the needle clamping angle. At a given picking frequency, the influence of the needle clamping angle on the seedling shedding rate is more significant than that of the spring stiffness coefficient.

As illustrated in Fig. 4(b), when the clamping angle of the seedling needle is 16°, the pot seedling shedding rate increases with the increasing spring stiffness coefficient. Meanwhile, it first decreases and then increases with the rising seedling picking frequency. The response surface exhibits a slower rate of change along the direction of seedling picking frequency and a faster rate of change along the direction of spring stiffness coefficient. When the seedling picking frequency is approximately 90 plants/min and the spring stiffness coefficient is around 400 N/m, the pot seedling shedding rate is relatively lower.

As depicted in Fig. 4(c), when the spring stiffness coefficient is approximately 400 N/m, the seedling shedding rate rises with the increasing seedling picking frequency and also increases with the increasing needle clamping angle. The response surface analysis indicates that the rate of seedling shedding varies more rapidly in the direction of the needle clamping angle and more slowly in the direction of the seedling picking frequency. Under a certain spring stiffness coefficient, the influence of the needle clamping angle on the seedling shedding rate is more significant than that of the seedling picking frequency.



(a) (b) (c)

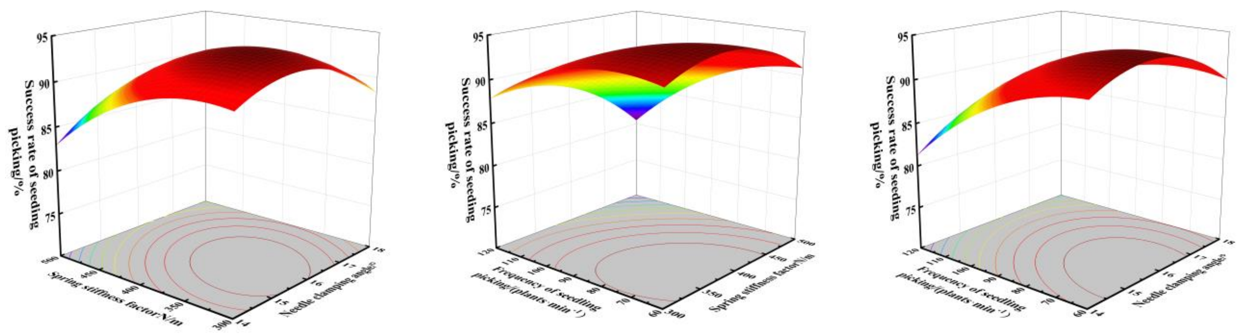
Fig. 4 – Effect of interaction factors on pot seedling shedding rate

Effects of interaction factors on seedling extraction success

The response surface of the seedling extraction success rate is presented in Fig. 5. As depicted in Fig. 5(a), when the seedling extraction frequency is 90 plants/min, the seedling extraction success rate decreases with the increasing seedling needle clamping angle and initially increases and then decreases with the rising spring stiffness coefficient. The response surface analysis reveals that the seedling extraction success rate exhibits a more rapid change along the direction of the spring stiffness coefficient and a relatively slower change along the direction of the needle clamping angle.

As shown in Fig. 5(b), when the clamping angle of the seedling needle is 16°, the success rate of seedling extraction increases with the increasing spring stiffness coefficient. Meanwhile, it initially increases and then decreases with the increasing seedling extraction frequency. The response surface analysis indicates a more rapid change in the direction of seedling extraction frequency and a relatively slower change in the direction of spring stiffness coefficient.

As depicted in Fig. 5(c), when the spring stiffness coefficient is set at 400 N/m, the success rate of seedling extraction initially increases and then decreases with the increasing seedling extraction frequency. Similarly, it first rises and then falls with the increasing needle clamping angle. The response surface analysis shows that the seedling extraction success rate varies gradually in the direction of the needle clamping angle, while it exhibits a relatively rapid change in the direction of the seedling extraction frequency. Given a certain spring stiffness coefficient, the impact of the seedling extraction frequency on the seedling extraction success rate is more pronounced than that of the seedling needle clamping angle.



(a) (b) (c)

Fig. 5 – Effect of interaction factors on seedling extraction success

Parameter optimization

To enhance the operational performance of the seedling extraction device, an optimization of its working and structural parameters is conducted. This optimization is aimed at achieving three primary goals: reducing the substrate loss rate, decreasing the seedling dropout rate, and increasing the success rate of seedling extraction. The optimization process employs the Optimization-Numerical module in Design-Expert V13.0.5 software to determine the optimal parameter settings. The objective functions and constraints for this optimization are outlined as follows:

$$\begin{cases} \min Y_1 \\ \min Y_2 \\ \max Y_3 \\ X_1 \in [-1,1] \\ X_2 \in [-1,1] \\ X_3 \in [-1,1] \end{cases} \tag{4}$$

The optimal parameter combinations were selected by the software Design-Expert.V13.0.5: spring stiffness coefficient of 376.81 N/m, a clamping angle of 15.6° and a seedling picking frequency of 89 plants/min. The model predicted the substrate loss rate of 3.94%, the pot seedling shedding rate of 2.01%, and a seedling-picking success rate of 94.05%.

Experimental validation

Using the optimized parameters (spring stiffness coefficient of 376.81N/m, seedling needle clamping angle of 15.6°, seedling picking frequency of 89 plants/min), the model validation experiments were carried out on the automatic seedling picking performance experimental table in the laboratory of agricultural machinery and equipment of Shandong University of Science and Technology, as shown in Fig. 6.

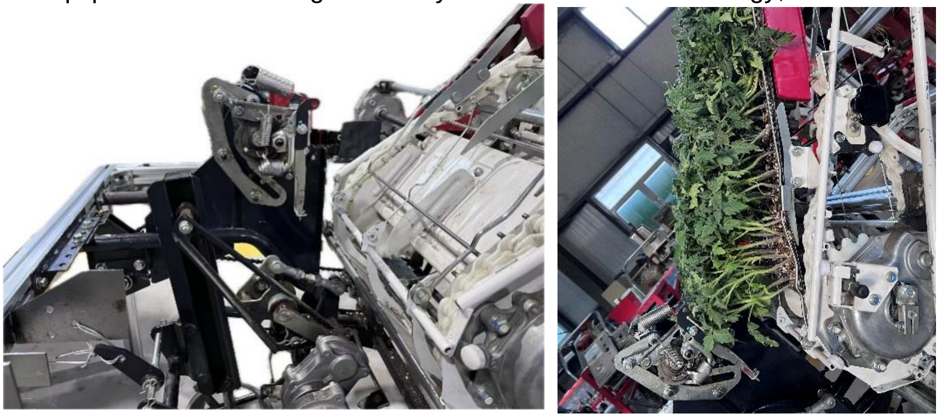


Fig. 6 – Automatic Seedling Picking Device Laboratory

To eliminate random errors and ensure the reliability of the results, five repeated tests were conducted, and the average values were calculated. Each test involved removing 72 seedlings from the entire tray, with the results summarized in Table 3. As can be seen, the average values of the substrate loss rate, pot seedling shedding rate, and seedling extraction success rate are 4.09%, 1.97%, and 93.94%, respectively. Notably, the error between the test value of the seedling extraction success rate and the optimized parameter value from the software is a mere 0.11%. This minimal discrepancy indicates that the selection of influencing factors on the quality of seedling extraction is reasonable and well - justified. Therefore, it can be concluded that the established performance optimization model of the automatic seedling picking device is correct and valid. Moreover, the obtained working and structural parameters fully meet the requirements for automatic seedling picking in tomato pot seedling machinery, ensuring both practical applicability and operational effectiveness.

Table 3

Results of seedling picking experiment under optimized conditions

Test No.	Substrate loss rateY_1/%	Pot seedling shedding rate Y_2/%	Success rate of seeding picking Y_3/%
1	3.41	0.83	95.76
2	3.53	1.21	95.26
3	4.26	1.95	93.79
4	4.71	2.75	92.54
5	4.54	3.13	92.33
Average value	4.09	1.97	93.94

CONCLUSIONS

1) This study investigated the cam motion process of the seedling gripper in a tomato pot seedling automatic extraction device, enabling the precise determination of cam movement parameters. By conducting a theoretical analysis of the forces acting on the root plug during the seedling-picking process, combined with the planting frequency of duckbill planting, a one-factor experiment was carried out using spring stiffness coefficient, seedling needle clamping angle, and seedling-picking frequency as the variables. The results indicated that these parameters had significant effects on the substrate loss rate, pot seedling shedding rate, and seedling-picking success rate.

2) A second - order rotary orthogonal combination test was performed on the seedling - picking device. Regression models between each factor and index were established, and the parameters were optimized using the response surface methodology. The optimal parameter combinations for the automatic seedling - picking device were determined as follows: the spring stiffness coefficient was 367.8 N/m, the clamping angle of the seedling needles was 15.6°, and the picking frequency was 89 plants per minute. Under these parameter combinations, the average substrate loss rate was calculated to be 4.09%, the average pot seedling shedding rate was 1.97%, and the average seedling extraction success rate was 93.94%. The results of the bench - top validation test were found to be in close agreement with the optimization results.

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