DESIGN AND EXPERIMENT OF A LONGITUDINAL AUXILIARY SEEDLING FEEDING DEVICE FOR A RAPESEED BLANKET SEEDLING TRANSPLANTER

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油菜毯状苗移栽机纵向辅助送苗机构设计与试验

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ABSTRACT

To address low qualified planting rate caused by inaccurate longitudinal seedling feeding in rapeseed blanket transplanter, a longitudinal auxiliary feeding device was designed. The working principle of the seedling feeding device is elucidated, and mathematical model of mechanics is established. The parameter range of the key components of the longitudinal auxiliary seedling feeding device was determined. A multi-factor test was implemented, evaluating spring tooth thickness (0.2-0.4 mm), height (65-75 mm), and quantity (6-8 units) as independent variables, and the longitudinal compression amount, uniformity coefficient of longitudinal seedling delivery, and qualified cutting rate as evaluation indexes. The test parameters were optimized using the comprehensive scoring method. The optimization results of the regression model derived from the quadratic orthogonal combination bench revealed test that when the thickness of the spring teeth was 0.29 mm, the height was 74.3 mm, and the number was 10, the longitudinal compression was 11.86 mm, the uniformity coefficient of longitudinal seedling delivery was 0.97, and the qualified cutting rate was 91.13%. It was verified that the longitudinal compression was 12.6 mm, the uniformity coefficient of longitudinal seedling delivery was 1.08, and the qualified rate of cutting was 93.6 %. The optimization results of the regression model verified by field experiments showed that the qualified planting rate was 92.35 %, the precision of seedling delivery was improved, and the feasibility of auxiliary seedling delivery device was verified.

摘要

针对油菜毯状苗移栽机因纵向送苗精度不足导致的栽植合格率低的问题，设计了一种纵向辅助送苗机构。阐述了该机构的工作原理并建立了力学模型，确定了关键部件的参数范围。采用多因素试验，以弹齿厚度（0.2~0.4 mm）、高度（65~75 mm）及数量（6~8 个）为自变量，以纵向压缩量、纵向送苗均匀性系数及切块合格率为评价指标，运用综合评分法优化试验参数。二次正交组合台架试验回归模型优化结果表明：当弹齿厚度 0.29 mm、高度 74.3 mm、数量 10 个时，纵向压缩量为 11.86 mm，纵向送苗均匀性系数为 0.97，切块合格率为 91.13%。验证试验结果为纵向压缩量 12.6 mm、纵向送苗均匀性系数 1.08、切块合格率 93.6%。田间试验验证优化模型后，栽植合格率达 92.35%，验证了方案的可行性。

INTRODUCTION

Rapeseed (*Brassica napus*), China's primary oilseed crop, was projected to cover 7.805 million hectares (hm²) by 2023 (*National Bureau of Statistics of China, 2024*). Seedling transplanting is the main way of rapeseed planting (*Liu X.Z., 2024*). *Wu et al. (2023)* from Nanjing Institute of Agricultural Mechanization, Ministry of Agriculture and Rural Affairs developed a rapeseed blanket seedling transplanting machine based on the operation principle of rice transplanter. This technology demonstrates exceptional clay soil adaptability in rice stubble fields and operational efficiency, facilitating widespread adoption across Yangtze Basin rice-rapeseed rotation systems. However, in the process of operation, due to the flexible and compressible material of rapeseed blanket seedling, the seedlings are placed in the seedling box through the longitudinal seedling feeding device for seedling transplanting, and the longitudinal seedling quantity is inconsistent, resulting in poor seedling quality and low planting quality (*Jiang et al., 2024*).

Modern transplanters employ three principal seedling delivery systems: (1) Mechanical drive positioning, through the forced movement of pure mechanical structures such as gears, cams, cranks and connecting rods, the seedlings are transferred and put in a fixed trajectory.

(2) Electropneumatic hybrid control, the PLC controller receives the sensor signal and instructs the pneumatic components such as solenoid valve and cylinder to cooperate with the motor to complete the orderly seedling picking and delivery. (3) Machine vision guided positioning (*Wu et al., 2013*), real-time shooting by industrial camera, accurate position of seedlings is identified by image algorithm, and high-precision servo actuator is guided to grab and release accurately. Early slow robotic arms were improved by five-bar linkage pick-up devices, these achieved 30 plants min^{-1} with 97% success (*Choi et al., 2002*) and later 60 plants min^{-1} with pneumatic grippers (*Brewer, 1994*). For ultra-high throughput, strand-feeding systems processing continuous honeycomb paper strands can achieve 100-140 plants min^{-1} (*Suggs et al., 1987*), though their success is critically dependent on perfect seedling uniformity. To accommodate variable pot dimensions, a two-stage conveyor system was developed, using ground-wheel feedback to decouple timing from forward speed and achieving 32 pots min^{-1} per row while tolerating ±3 mm pot-diameter variation (*Kumar et al., 2011, 2012*). The choice of end-effector is also crucial, as studies show gripper selection must be based on seedling morphology rather than machine design, with two-finger grippers achieving 95% success across multiple species (*Jorg et al., 2021*). PF2R automatic vegetable transplanter (*Yanmar, 2016; Liu et al., 2010*) produced by YANMAR Company and PZP-80 automatic vegetable transplanter (*Candelas et al., 2015*) produced by Japan ISEKI Company both use pure mechanical drive to realize horizontal and vertical seedling feeding, which requires high machining accuracy of parts. Commercial implementations include ISEKI's PVHR2-E18 (Japan) and PC-21 (Netherlands), which integrate the method of mechanical, electrical and gas control (*Yu et al., 2014*). This method has wide applicability, high precision of seedling delivery, large volume and high price. The Pic-O-Mat GR2700 automatic greenhouse plug tray transplanter (*Yang et al., 2018*) produced by VISSES company in the Netherlands and the Futura automatic transplanter (*Fang et al., 2021*) with machine vision function developed by Ferrari company in Italy use visual positioning to realize seedling delivery. This method has high intelligence, high precision and efficiency of seedling delivery, sensitive to vibration and high price. In China, *Yu et al. (2024)* proposed a four-link longitudinal disc feeding device driven by cam connecting rod and sector gear. This device further improves the accuracy and stability of the longitudinal disc feeding of vegetable pot seedling transplanter, but it needs to be matched with the size of the tray to plan the trajectory of the tray, and the versatility is poor. Xue et al. (2020) designed the longitudinal seedling feeding device of the ratchet linkage pot seedling transplanter. The device has simple structure, accurate positioning, and has a certain compensation effect on the cumulative error, but the ratchet manufacturing requirements are higher. *Na et al. (2015)* designed a ratchet gear type longitudinal seedling feeding device for rice pot seedling transplanting. The device has accurate transmission ratio, good working reliability, no cumulative error and stable operation, but it has high requirements for processing and installation. *Hu et al. (2022)* designed a bidirectional progressive seedling feeding device for rapeseed matrix transplanting machine. The device is controlled by single-chip microcomputer, which has simple structure, poor stability and reliability, and is easy to produce cumulative error. The high-speed rice transplanter adopts mechanical drive, and the slider and the seedling box realize horizontal reciprocating motion under the action of double helix (*Yang et al., 2003*). When the seedling box moves to the left and right ends, the one-way ratchet will be plucked at an angle, so as to realize a longitudinal intermittent motion, and the seedling picking device only needs to be fixed at the seedling picking point. Affected by factors such as machine vibration, seedling blanket quality, and moisture content of seedling blocks, seedlings are prone to sliding or extrusion deformation, resulting in inaccurate longitudinal seedling feeding (*Li et al., 2018; Zhao et al., 2011*). *Du et al. (2014)* developed a longitudinal precision seedling feeding device for mechanical trans-planting of bowl blanket seedlings, using intermittent swing rod device, four-bar device, double ratchet device, and double-sided synchronous belt. However, the device is only suitable for longitudinal feeding of bowl blanket seedling trays with fixed sizes. *Yu et al. (2015)* and *Na et al. (2015)* developed a precise longitudinal seedling feeding device for the pot seedling transplanter. The double-sided synchronous belt and double ratchet wheel, ratchet wheel gear and chain wire device were used to realize the fixed-size longitudinal seedling feeding of the pot seedling transplanter. *Qiu et al. (2012)* and *Zhao (2016)* designed a seedling feeding device for vegetable pot seedling automatic transplanting machine. Through the coordination of horizontal and vertical seedling feeding device, the efficient automatic seedling feeding function was realized, and its performance was verified by experiments. The maximum feeding speed can reach 120 plants / min. *Jiang et al. (2024)* optimized the mechanical parameters of rapeseed blanket seedling and the structural parameters of the longitudinal seedling feeding device, which significantly improved the accuracy of seedling feeding. However, the design can be further optimized to make the mechanized transplanting of rapeseed blanket seedling more accurate.

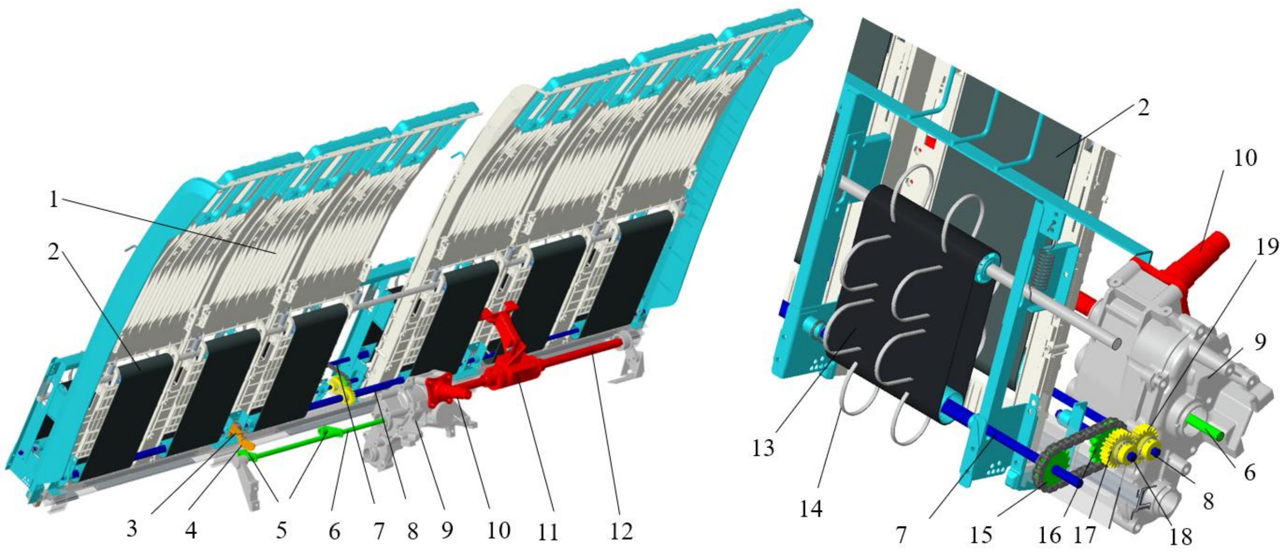
It can be seen that there is still a lack of relevant research on the precise longitudinal seedling feeding of rapeseed blanket seedling by one-way ratchet intermittent seedling feeding, and it is necessary to create a new precise longitudinal seedling feeding device.

In the process of seedling delivery, the existing rapeseed blanket seedlings are easy to be compressed because the substrate is flexible material, and the vertical freedom of seedlings in the seedling delivery system is not constrained. Under the influence of operation vibration, the vertical seedling delivery is inaccurate, which leads to the problems of high seedling taking rate, high seedling injury rate and low qualified planting rate. To solve this problem, this paper designs a vertical auxiliary seedling delivery mechanism device on the original vertical seedling delivery mechanism device, which forms clamping and conveying with the original seedling delivery device to realize accurate seedling delivery. The mathematical model of seedling feeding system was established by mechanical analysis, and the structural parameters of longitudinal auxiliary seedling feeding mechanism were optimized by bench test, which was verified by field test. The research results provide theoretical basis and data support for the innovation and optimization design of seedling feeding mechanism of automatic transplanter.

MATERIALS AND METHODS

Structure and working principle of the longitudinal auxiliary seedling feeding device

The structure of the longitudinal auxiliary seedling feeding device is shown in Figure 1. The device mainly consists of seedling box, longitudinal seedling feeding device, longitudinal auxiliary seedling feeding device, transmission device and transverse seedling feeding device.



(a) *(b)*

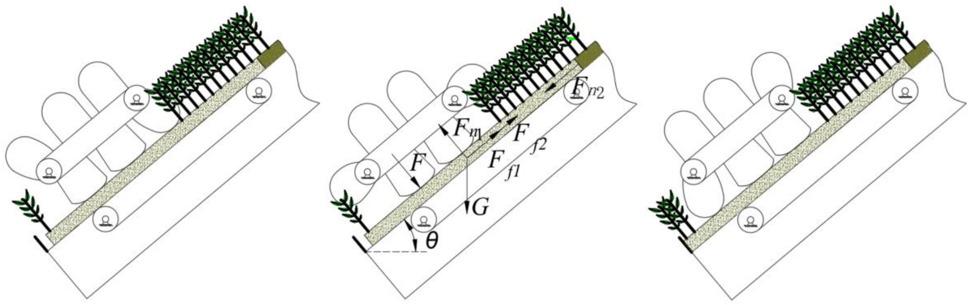
Fig. 1 - Schematic diagram of the planting mechanism of the rapeseed blanket seedling transplanter

1. Seedling box; 2. Seedling feeding belt; 3. One-way ratchet; 4. Toggle lever; 5. Cam; 6. Drive shaft Ⅰ; 7. Drive shaft Ⅳ; 8. Drive shaft II; 9. Transmission box; 10. Power input shaft; 11. Slider; 12. Spiral shaft; 13. Auxiliary seedling feeding belt; 14. U-shaped spring teeth; 15. Sprocket II; 16. Sprocket Ⅰ; 17. Gear II; 18. Drive shaft Ⅲ; 19. Gear Ⅰ. (a) Rear view; (b) Front view (partial)

Its working principle is that blanket seedlings are placed on the seedling feeding belt, and the upper part is pressed by U-shaped spring teeth, and the rotating power drives the power input shaft, and the spiral shaft and the drive shaft I are respectively driven by the power of the transmission box. The spiral shaft is connected with the slider to drive the seedling box to move laterally., so as to drive the seedling box to move laterally, and at the same time, the toggle lever also moves laterally. The drive shaft I drives the cam to rotate. When the seedling box moves laterally to the limit positions at both ends, the cam moves the shifting lug to rotate the seedling feeding belt; the one-way ratchet wheel drives the drive shaft II to rotate for a fixed angle, so as to drive the seedling feeding belt to move downward for a fixed distance; at the same time, the drive shaft II drives the drive shaft III through the meshing transmission of the gear I and the gear II, and drives the drive shaft IV through the chain transmission of the sprocket I and the sprocket II, and the drive shaft IV drives the auxiliary seedling feeding belt to move for a fixed distance, which is the same as that of the seedling feeding belt, thus achieving the purpose of clamping and feeding seedlings downward.

Design and Analysis of a Longitudinal Auxiliary Seedling Feeding Device for a Rapeseed Blanket Seedling Transplanter

When the rapeseed blanket seedling transplanting machine is operating, the seedling pieces will be compressed by the U-shaped spring teeth on the longitudinal auxiliary seedling feeding device on the lower seedling feeding belt. According to the distribution of the spring teeth, three stress states can be analyzed. Taking the spring teeth distributed six times a week as an example, the three states are shown in Figure 2.



(a) (b) (c)

Fig. 1 - Three state force diagram of longitudinal auxiliary seedling feeding device

(a) the first stress state; (b) the second stress state;(c) the third stress state

Fig. 2 shows three stress states of rapeseed blanket seedlings when they are put into the seedling feeding system. Analysis of Figure 2 reveals that the second stress state (Figure 2b) has the smallest elastic tooth force. To prevent seedling slippage, the critical elastic tooth force required for stable grasping is determined through force equilibrium analysis using Equation (1).

$$\begin{cases} F_{f1}+F_{f2}\text{-}F_{n2}\text{-}G\sin\theta=0 \\ F_{n1}\text{-}nF\text{-}G\cos\theta=0 \\ F_{f1}=\mu_1 F_{n1} \\ F_{f2}=n\mu_2 F \\ F_{n2}\left(1\text{-}\mu_3\right)G\cos\theta \end{cases} \tag{1}$$

where: F_{f1} is the friction between the conveyor belt and the lower seedling, [N];

F_{f2} is the friction force between the spring teeth and the lower seedlings, [N];

G is the seedling gravity, [N];

μ_1 is the friction coefficient between the conveyor belt and the lower seedling;

μ_2 is the friction coefficient between the elastic tooth and the lower seedling;

μ_3 is the friction coefficient between the seedling box and the upper seedling;

F_{n1} is the supporting force of the seedling box to the lower seedlings, [N];

F_{n2} is the force of the upper seedling to the lower seedling, [N];

θ is the angle between the seedling box and the ground, [°];

F is the force of a single elastic tooth on the seedling under the minimum stress state of the seedling, [N];

n is the number of elastic teeth distribution under the minimum stress state of the seedlings.

Total weight of the single-disc seedling was about 2 kg, the inclination angle of the seedling box was θ = 50.14° (*Jiang et al., 2024*). Reference agricultural machinery design manual take μ_1 = 0.8, μ_3 = 0.7 (*Zhang, 2007*). The μ_2 = 0.441 was measured by the slope method. In the second stress state, the number of spring teeth is n = 4, and the parameters are brought into Equation (1) to obtain the minimum force F = 2.27 N of a single spring tooth on the seedling.

The key components of the longitudinal auxiliary seedling feeding device: spring teeth and conveyor belt are designed. As shown in Fig. **2**, the main parameters of the conveyor belt include the diameter of the pulley D and the center distance between the two pulleys a; the spring-tooth material is 65Mn, and its main parameters include the thickness of spring-tooth *A*, the height of spring-tooth *B*, the span of spring-tooth *C*, the width of spring-tooth *E* and the number of spring-tooth n.

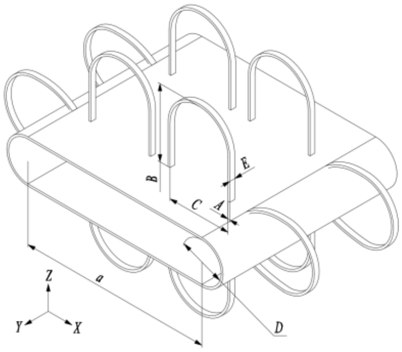


Fig. 2 - Main parameters of longitudinal auxiliary seedling feeding device

Spring teeth thickness is the key influence parameter of seedling force. The universal material testing machine (3343, INSTRON, Norwood, MA, USA, 0 ~ 1 kN) was used to measure and draw the force-compression curves of different elastic tooth thicknesses of 0.1 ~ 0.5 mm. The test conditions are shown in **Error! Reference source not found.**.

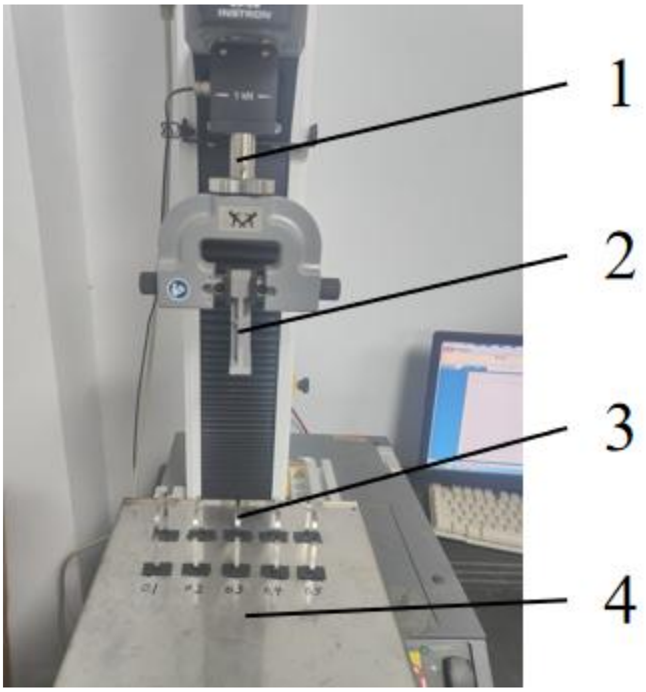


Fig. 4 - Test conditions of spring tooth

1. universal material testing machine; 2. force piston;3. spring teeth;4. metal plate

In the test, the spring teeth with different thicknesses were bonded to the metal plate, and the force piston was used to press the upper part of the spring teeth at a speed of 60 mm / min. When the displacement reached 25 mm, the test was terminated, and the force-displacement curve was obtained, as shown in Fig.5.

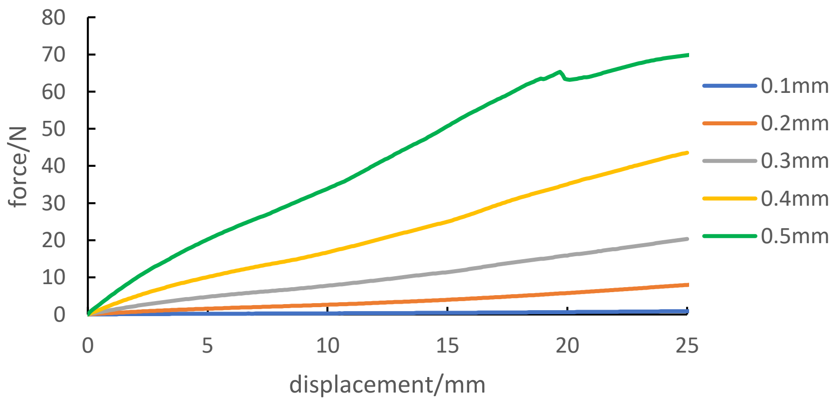


Fig. 5 - Force and displacement curves of different spring tooth thickness

Through the data curve obtained from the test and the appeal, it can be seen that when the elastic tooth thickness is 0.1 mm, the force is only 0.9 N when the compression amount reaches 25 mm, which does not meet the minimum elastic tooth non-slip force F requirement. When the thickness of the spring tooth is 0.5 mm, the compression amount reaches 20 mm, the force reaches 63.22 N, which exceeds the maximum yield force of the seedling, and the seedling is squeezed and damaged. Therefore, the thickness of the spring teeth is 0.2 ~ 0.4 mm.

When the spring teeth are transferred to the pulley, the height will be reduced, thereby reducing the impact of the retaining rod on the operation of the device. The seedling height of rapeseed blanket seedling is 80 ~ 90 mm, and the tip of the elastic tooth should be in contact with the seedling piece to indicate that the seedling piece should be clamped. Because the top 10 ~ 20 mm part of the seedling top is flexible, the conveyor belt can contact the seedling and play the same role as the original seedling frame. In order to reduce the distance between the lower end and the seedling door, the height of the elastic tooth B is 65 ~ 75 mm.

The number of spring teeth set on the conveyor belt is related to the length of the conveyor belt and the span of the spring teeth. In order to ensure that the seedlings are still pressed by external force to prevent the seedlings from overturning when they are cut to the end, the installation position of the longitudinal auxiliary seedling feeding device is reduced as much as possible, and the interference between the spring teeth and the bottom seedling retaining rod is prevented. The spring teeth are deformed at the corner of the conveyor belt and the height of the spring teeth is reduced. The larger the span of the spring tooth, the larger the deformation during the turning, but the stronger the tear at the adhesion between the spring tooth and the conveyor belt, so the span of the spring tooth should be smaller than the semicircle circumference of the conveyor belt, that is, $C < \pi D / 2$, the diameter of the pulley D is designed to be 40 mm, and C < 62 mm is calculated. In order to ensure sufficient deformation, the span of the spring tooth C is 60 mm. The center distance a of the two pulleys is designed to be 180 mm, and the circumference of the whole belt is about 486 mm. Each column can be distributed with a maximum of 8 elastic teeth. In order to make the connection between the elastic teeth and the belt more reliable, a gap should be left between the elastic teeth to facilitate bonding, and it is more appropriate to have 6 elastic teeth in each column. The transverse distribution of spring-tooth should avoid the theoretical distance of the plant, so as to reduce the possibility of pressing seedlings. Due to the agronomic characteristics of blanket seedlings, it is difficult to ensure that the theoretical distance of seedling spacing is 20 mm. Therefore, the width of spring-tooth E is 5 mm, and the number of distribution should not take too many two columns. Therefore, the number of spring teeth is 8 ~ 12.

Performance optimization test of longitudinal auxiliary seedling feeding device

The length × width = 580 mm × 280 mm (Figure 6), the seedling age was 35 days, the average moisture content was 72 % (error ± 0.5), the average thickness of the seedling was 22 mm (error ± 0.2), and the seedling height was 80 ~ 90 mm.

Fig. 6 - Rapeseed blanket seedling

The experiment adopted the multifunctional rapeseed blanket seedling transplanting stand jointly developed by Nanjing Agricultural Mechanization Research Institute of Ministry of Agriculture and Rural Affairs and Changlin Co., LTD., China National Machinery Industry Group (Fig.7) (*http://www.changlin.com.cn/, 2025*). The bench has the functions of ditching, planting, and soil covering. The rotation speed of each part can be adjusted and tested, and each part can be replaced to carry out the test of rapeseed blanket seedling transplanting.

Fig. 7 - Multifunctional rapeseed blanket seedling transplanting bench

1. operating console; 2. electric control box; 3. forward motor; 4. single-row seedling box; 5. longitudinal auxiliary seedling feeding device; 6. ditching drive motor; 7. planting device; 8. chassis; 9. soil trough

The following requirements need to be met when selecting rapeseed blanket seedling: minimize the compression of seedling; in the process of longitudinal seedling feeding, the uniformity of longitudinal seedling feeding distance, seedling row spacing and longitudinal cutting width should be ensured to avoid secondary compression or sliding. To ensure the integrity of the seedlings, there should be no matrix fragmentation. The thickness, height and number of spring teeth were taken as the test factors, and the longitudinal compression Y_1, the uniformity coefficient of longitudinal seedling delivery Y_2 and the qualified rate of cutting Y_3 were taken as the evaluation indexes.

The rapeseed blanket seedling was placed on the seedling box, and the seedlings were transferred to the seedling door. The length of the rapeseed blanket seedling placed on the seedling box was measured by a tape measure (0 ~ 5 m measurement accuracy 1 mm), and the standard length was subtracted from the measured length to obtain the longitudinal compression amount Y_1.

The uniformity coefficient of longitudinal seedling delivery Y_2, when a row of seedlings is taken, the seedlings are moved downward and marked on the edge of the seedling box. The i-th longitudinal transfer distance S_{mi} of seedlings was measured. The theoretical longitudinal transfer distance S_p of this experiment was 17 mm by actual measurement, and the uniformity coefficient Y_2 of longitudinal seedling delivery was calculated using Equation (2).

$$\begin{cases} Y_2=\sqrt{\dfrac{\sum_{i=1}^{n}\left(X_i-\bar{X}\right)^2}{n}} \\ X_i=\left|S_p-S_{mi}\right| \end{cases} \tag{2}$$

where:

X_i is the i-th longitudinal transfer distance deviation, [mm]; S_p is the theoretical longitudinal transfer distance; and n is longitudinal seedling picking times of blanket seedlings; $\bar{X}$ is average value of longitudinal transfer distance, [mm].

The qualified rate of cutting block Y_3

The theoretical cutting block size is obtained according to the cutting parameters. If the mass loss of the seedling block is less than 20 %, the seedling block is considered to be qualified. In order to improve the test efficiency, 50 seedling blocks were randomly selected from each blanket seedling and the plant was cut off to observe the qualified rate of the cut block.

The qualified rate of cutting is the proportion of seed blocks without serious damage, which can be calculated using Equation (3).

$$Y_3 = \frac{N_c}{N} \times 100\% \tag{3}$$

where N_c is the number of qualified seedlings; and N is the number of sample seedlings tested in the trial.

Taking the thickness, height and number of spring teeth as the test factors, the longitudinal compression amount, the uniformity coefficient of longitudinal seedling delivery and the qualified rate of cutting block as the test indexes, the three-factor three-level quadratic orthogonal combination test was carried out by using Design-Expert 13 software. The experimental factors and coding are shown in Table 1.

Table 1

Test factors and coding

Coding	Thickness of spring teeth X_1 [mm]	Height of spring teeth X_2 [mm]	Number of spring teeth X_3
-1	0.2	65	8
0	0.3	70	10
1	0.4	75	12

RESULTS

Test results and analysis

The non-significant variables were eliminated by analyzing the test data, and the multivariate nonlinear regression model of longitudinal compression Y_1, uniformity coefficient of longitudinal seedling delivery Y_2 and qualified cutting rate Y_3 was established as follows:

$$\begin{cases} Y_1 = 15.2 - 1.5X_1 - 4.5X_2 - 2.5X_3 + 1.25X_1X_2 + 1.25X_1X_3 - 1.48X_1^2 + 1.02X_2^2 + 1.53X_3^2 \\ Y_2 = 1.13 - 0.1162X_1 - 0.24X_2 - 0.0563X_3 - 0.075X_1X_2 + 0.035X_2X_3 + 0.1313X_1^2 + 0.0437X_2^2 + 0.0813X_3^2 \\ Y_3 = 94.8 - 2.25X_1 - 4.25X_2 - X_3 - 1.5X_1X_2 - 2.15X_1^2 \end{cases} \tag{4}$$

In view of the inherent contradiction between these three indicators, this study uses a comprehensive scoring method to determine the optimal solution. Before calculating the comprehensive score, the indicators were standardized.

The normalized equation used to achieve the minimum longitudinal compression and the minimum uniformity coefficient of longitudinal seedling delivery (*Jiang et al.,2024*) is as follows:

$$d_{Y_1\text{-}i} = \frac{Y_{1\max} - Y_{1i}}{Y_{1\max} - Y_{1\min}} \tag{5}$$

$$d_{Y_2\text{-}i} = \frac{Y_{2\max} - Y_{2i}}{Y_{2\max} - Y_{2\min}} \tag{6}$$

where $d_{Y1\text{-}i}$ is the normalized value of the maximum longitudinal compression allowed in each group of tests; $Y_{1\max}$ is the maximum longitudinal compression allowed in the tests, [mm]; $Y_{1\min}$ is the minimum longitudinal compression in the tests, [mm]; Y_{1i} is the test value of the compression in each group of tests, [mm]; $d_{Y2\text{-}i}$ is the normalized value of the maximum coefficient of variation in seedling conveying distance allowed in each group of tests; $Y_{2\max}$ is the maximum value of the coefficient of variation in the seedling conveying distance in the tests; $Y_{2\min}$ is the minimum value of the coefficient of variation in the seedling conveying distance in the tests; and Y_{2i} is the test value of the coefficient of variation in the seedling conveying distance in each group of tests.

The normalization equation used to achieve the maximum qualified cutting rate is as follows:

$$d_{Y_3-i} = \frac{Y_{3i} - Y_{3\,min}}{Y_{3\,max} - Y_{3\,min}} \tag{7}$$

where d_{Y_3-i} is the normalized value of the minimum qualified-block-cutting rate allowed in each group of tests;

Y_{3max} is the maximum value of the qualified-block-cutting rate in the tests, [%]; Y_{3min} is the minimum value of the qualified-block-cutting rate in the tests, [%]; and Y_{3i} is the test value of the qualified-block-cutting rate in each group of tests, [%].

Accurate longitudinal seedling conveying is a critical aspect in the design of seedling conveying devices and a prerequisite for achieving optimal planting quality. Therefore, the weighted coefficients for the longitudinal compression and the coefficient of variation in seedling conveying distance in this optimization test are slightly higher compared to that for the qualified-block-cutting rate, with values of 0.4, 0.4, and 0.2, respectively. The comprehensive score is calculated as follows:

$$D_{v\text{-}i}=\left(0.4d_{Y_1\text{-}i}+0.4d_{Y_2\text{-}i}+0.2d_{Y_3\text{-}i}\right)\times 100 \quad (8)$$

The results of each experimental design and evaluation index are shown in Table 2.

Table 2

Experimental design and results

Number	X_1 [mm]	X_2 [mm]	X_3	Y_1 [mm]	Y_2	Y_3 [%]	Overall score D_v
1	-1	0	-1	20	1.53	96	34.69
2	-1	-1	0	22	1.61	98	28
3	-1	1	0	11	1.25	92	67.71
4	-1	0	1	13	1.37	92	56.06
5	0	-1	-1	25	1.57	98	22.11
6	0	1	-1	16	1.05	92	64.9
7	0	0	0	15	1.16	96	67.49
8	0	0	0	15	1.11	96	70.13
9	0	0	0	14	1.1	94	70.46
10	0	0	0	16	1.15	94	62.5
11	0	0	0	16	1.13	94	63.55
12	0	-1	1	20	1.39	98	44.91
13	0	1	1	10	1.01	88	77.29
14	1	0	-1	15	1.27	90	53.13
15	1	-1	0	16	1.51	96	46.41
16	1	1	0	10	0.85	84	80
17	1	0	1	13	1.2	90	62.15

Table 3

Variance analysis

Source of variation	*p*-Value / Y_1	*p*-Value / Y_2	*p*-Value / Y_3
Model	<0.0001**	<0.0001**	<0.0001**
X_1	0.001**	<0.0001**	0.0002**
X_2	<0.0001**	<0.0001**	<0.0001**
X_3	<0.0001**	0.0006**	0.0171*
X_1X_2	0.0153*	0.0008**	0.0132*
X_1X_3	0.0153*	0.1369	0.064
X_2X_3	0.5438	0.0348*	0.064
X_1^2	0.0062**	<0.0001**	0.0019**
X_2^2	0.0314*	0.0122*	0.7452
X_3^2	0.0052**	0.0004**	0.1863
Lack of fit	0.5927	0.4046	0.8395

*Note: ** highly significant (P < 0.01); * significant (P < 0.05).*

The test results were analyzed (Error! Reference source not found.). In the model Y_1, X_1, X_2, X_3, X_1^2 and X_3^2 were highly significant, and X_1X_2, X_1X_3 and X_2^2 were significant. In the model Y_2, X_1, X_2, X_3, X_1X_2, X_1^2 and X_3^2 are highly significant, and the variables X_2X_3 and X_2^2 are significant. In model Y_3, X_1, X_2 and X_1^2 were highly significant, and X_3 and X_1X_2 were significant.

Through data processing, the response surface of the highly significant and significant interaction between the factors on the test index is obtained, as shown in Figure 8.

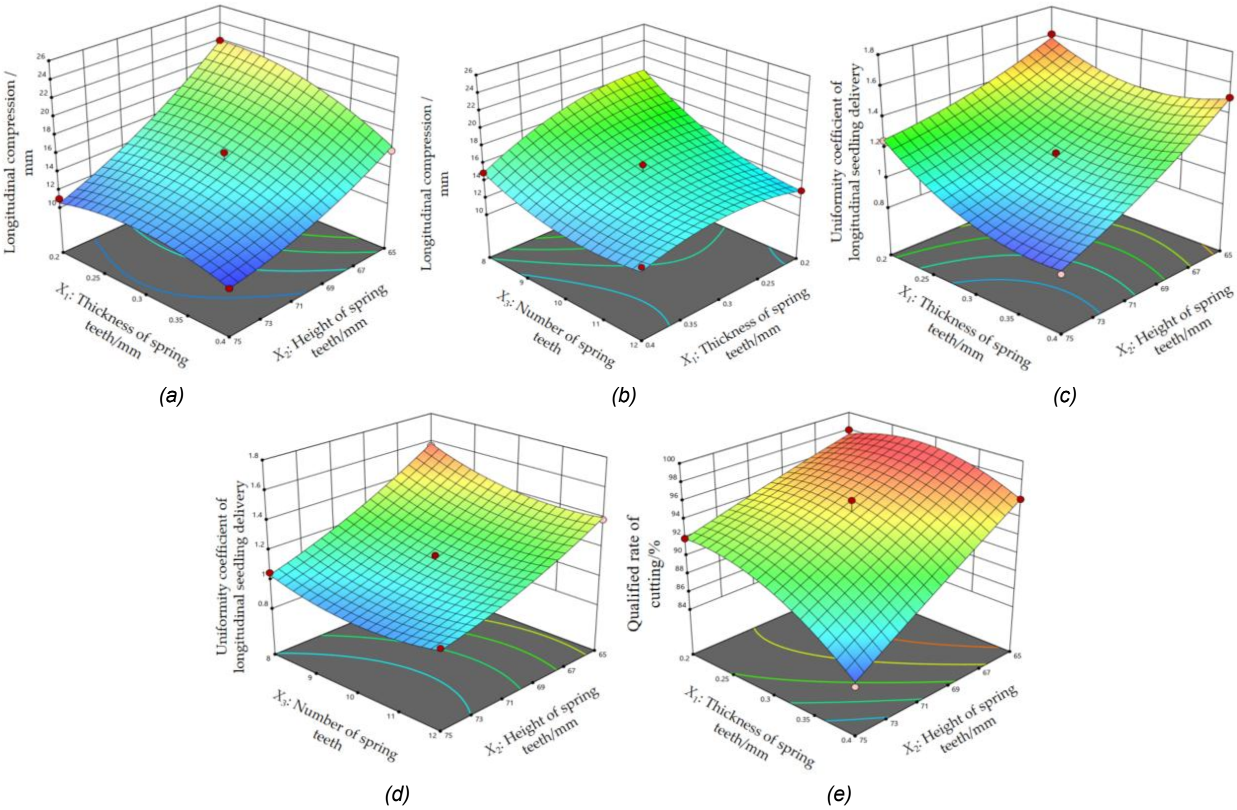


Fig. 8 - Experimental factor response surface

(a) the effect of spring teeth thickness and height on longitudinal compression; (b) the effect of spring teeth thickness and number on the longitudinal compression; (c) the effect of spring teeth thickness and height on the uniformity coefficient of longitudinal seedling delivery; (d) the effect of spring teeth number and height on the uniformity coefficient of longitudinal seedling delivery; (e) the effect of spring teeth thickness and height on the qualified cutting rate

The test results show that in Figure 8. (a) The thickness of different spring teeth will increase the longitudinal compression of the seedlings with the decrease of the height of the spring teeth. The thinner the thickness of spring teeth, the more obvious the longitudinal compression of the seedlings. (b) The thinner the thickness of spring teeth, the more obvious the longitudinal compression of the seedlings with the decrease of the number of spring teeth; (c) The thickness of different spring teeth will increase the uniformity coefficient of longitudinal seedling delivery of the seedlings with the decrease of the height of spring teeth. The thicker the thickness of spring teeth, the more obvious the uniformity coefficient of longitudinal seedling delivery of the seedlings. (d) The number of different spring teeth will increase the uniformity coefficient of longitudinal seedling delivery of the seedlings with the decrease of the height of spring teeth. The smaller the number of spring teeth, the more obvious the uniformity coefficient of longitudinal seedling delivery of the seedlings. (e) With the decrease of the height of spring teeth, the thickness of spring teeth will increase the qualified rate of cutting. The thicker the thickness of spring teeth, the more obvious the change of the qualified rate of cutting.

The comprehensive scoring model was optimized using Design-Expert 13.0 software. The optimization results showed that the predicted optimization parameters were as follows: the thickness of spring teeth was 0.29 mm, the height of spring teeth was 74.3 mm, and the number of spring teeth was 10. Using these parameters, the transplanter achieved a comprehensive score of 78.88, the longitudinal compression was 11.86 mm, the uniformity coefficient of longitudinal seedling delivery was 0.97, and the qualified cutting rate was 91.13 %. The obtained operation quality indicators meet the relevant technical standards in the industry standards and agronomic production requirements of dryland transplanters, indicating that the seedling feeding and cutting performance using optimized parameters achieves better working performance.

Verification test

The optimized parameters were used for the verification test, and the same index measurement method was repeated for five times and the average value was obtained, as shown in Table 4. The final longitudinal compression amount was 12.6 mm, the uniformity coefficient of longitudinal seedling delivery was 1.08, and the qualified rate of cutting was 93.6 %.

Table 4

Verification test results

Test	The longitudinal compression [mm]	The uniformity coefficient of longitudinal seedling delivery	The qualified rate of cutting [%]
1	14	1.12	94
2	12	1.05	96
3	15	0.98	92
4	10	1.07	94
5	12	1.16	92
Average value	12.6	1.08	93.6

The measured values of each index are not different from the predicted values, indicating that the selection of optimization results is reasonable and has achieved better results, in line with the application standards.

Field test verification

The experiment was carried out in Xixiashu Town, Xinbei District, Changzhou City, Jiangsu Province in November 2024 (Figure 9). The tractor model is Dong-fanghong 1204, the operating speed is 2.88 ~ 4.32 km / h, the average firmness of the soil depth of 50 mm in the test site before transplanting is 82.2 kPa, the average moisture content is 23.46 %, the thickness of the elastic teeth is 0.29 mm, the height of the elastic teeth is 74.3 mm, and the number of elastic teeth is 10. The quality of seedling delivery ultimately affects the qualified planting rate of the transplanter, and the field test index is the qualified planting rate (*Wu et al.,2020*). Three field experiments were repeated and the average results were taken, as shown in Table 5. The qualified rate of planting was 92.35 %, and the quality of operation was much higher than the requirements of agricultural industry standards.

Fig. 9 - Field experiment

Table 5

Field test results

Test	Number of samples	Number of exposed seedlings	Number of missed seedlings	Number of seedlings planted	Number of damaged seedlings	Qualified planting rate [%]
1	200	4	3	5	3	92.5
2	200	4	4	6	2	92
3	201	2	4	5	4	92.54
Average value	200.33	3.33	3.67	5.33	3	92.35

CONCLUSIONS

A longitudinal auxiliary feeding device was designed, and its mathematical model was established. It was found that the minimum force of a single spring tooth on seedlings was f = 2.27 N. The thickness of the elastic teeth is 0.2~0.4mm, the height of the elastic teeth is 65~75mm, and the number of elastic teeth is 8~12.

The multifunctional rapeseed blanket seedling transplanting bench was used to optimize the performance of the longitudinal auxiliary seedling feeding device. The single factor test was used to further reduce the range of spring-tooth thickness. Then, the three-factor three-level quadratic orthogonal combination test method was used. The spring-tooth thickness, spring-tooth height and spring-tooth number were used as test factors, and the longitudinal compression amount, the uniformity coefficient of longitudinal seedling feeding amount and the qualified cutting rate were used as evaluation indexes. The comprehensive scoring method was used to optimize the parameters. The regression model optimization results showed that when the thickness of spring teeth was 0.29 mm, the height of spring teeth was 74.3 mm, and the number of spring teeth was 10. The longitudinal compression was 11.86 mm, the uniformity coefficient of longitudinal seedling delivery was 0.97, and the qualified cutting rate was 91.13 %. It was verified that the longitudinal compression was 12.6 mm, the uniformity coefficient of longitudinal seedling delivery was 1.08, and the qualified cutting rate was 93.6 %.

According to the optimization results, the field experiment was carried out to verify that when the thickness of spring teeth was 0.29 mm, the height of spring teeth was 74.3 mm, and the number of spring teeth was 10, the qualified planting rate was 92.35 %.

The longitudinal compression of the seedlings was further reduced, the uniformity of the longitudinal seedling feeding was improved, and the cutting quality was improved. Improving the accuracy of vertical seedling delivery can improve the utilization rate of seedlings, reduce costs and improve the survival rate of seedlings after planting. In addition, the conveying method of the longitudinal seedling feeding device can be further optimized. For example, by cultivating blanket seedlings with convex and concave shapes at the bottom, and designing a conveyor belt that contacts and matches the bottom of the blanket seedlings to make them mesh during the conveying process, the longitudinal compression deformation caused by self-weight is controlled, and the accuracy of seedling feeding is improved by combining agronomy with agricultural machinery.

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