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Mechanical Characteristics Testing and Parameter Optimization of Rapeseed Blanket Seedling Conveying for Transplanters

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Abstract: Rapeseed blanket seedling transplanters have developed rapidly due to their high efficiency and adaptability to the soil in many areas of China. However, during the transplanter's longitudinal seedling conveying process, seedling blanket compression leads to inaccurate conveying and thus declined seedling picking performance. In this paper, a mechanical compression test was carried out on rapeseed seedling blankets. The longitudinal compression force of the rapeseed seedling blanket on a transplanter was calculated through mechanical analysis. A compression model of the rapeseed seedling blanket was established to determine how the blanket's mechanical characteristics and the device's structural parameters affect blanket compression. In addition, with the index of longitudinal compression Y_1, the coefficient of variation in the longitudinal seedling conveying distance Y_2, and the qualified-block-cutting rate Y_3, the interactive influence between the seedling tray tilt angle A, the seedling blanket moisture content B, and the seedling blanket thickness C were analyzed using response surface analysis. Aiming to reduce blanket compression and enhance the accuracy of longitudinal seedling conveying and block-cutting quality, the optimized results show that the predicted optimal parameters were a 50.14° seedling tray tilt angle, a 71.86% seedling blanket moisture content, and a 22.13 mm seedling blanket thickness. Using these optimized parameters, the transplanter achieved a blanket longitudinal compression of 18.17 mm, a coefficient of variation in the longitudinal seedling conveying distance of 1.142, and a qualified-block-cutting rate of 90%. Subsequently, a validation test was performed, revealing a high degree of conformity between the optimization model and the experimental data. Thus, the predicted optimal parameters can provide significantly reduced compression and a high seedling conveying performance. The results of this study provide theoretical and empirical support for the optimized design and operation of mechanized rapeseed blanket seedling transplanting.

Keywords: compression; rapeseed blanket seedling; transplanter; conveying mechanism; optimization

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1. Introduction

Rapeseed (Brassica napus) is the most important oil crop in China, with an annual planting area of about 7 million hectares, with its area and total output being among the top in the world. The Yangtze River Valley is the largest planting region of winter rapeseed in the world. The region mainly implements a cropping pattern of rice–rape rotation. Rapeseed blanket seedling transplanting represents an innovative dryland transplanting method that is efficient and suitable for the relevant soil conditions. The method found initial experimental success in rapeseed applications and was subsequently expanded to encompass Chinese cabbage, stevia rebaudiana, and capsicum [1,2]. In this method, blanket seedlings, cultivated through the chemical control methods, were transplanted by a special blanket seedling transplanter as follows: a seam was cut in the soil, and the machine automatically conveyed the seedlings; then, the seedling blanket was cut into blocks, and the seedlings were picked up, planted into the seam, and finally covered with soil. The planting frequency of a rapeseed blanket seedling transplanter exceeded 200 times/min/row [3–5]. Wu et al. [6] designed a 2ZY 6 rapeseed blanket seedling transplanter along with its key components and conducted experiments on soils with varying moisture contents ranging from 17.6% to 30%, achieving a planting success rate of 85% on clayey soils. Building upon this foundation, Tang et al. [7] designed a combination rapeseed blanket seedling transplanter capable of simultaneously performing both tillage and transplanting, with a working efficiency reaching 4–6 mu per hour. Jiang et al. [8] conducted experimental studies on the physical soil conditions suitable for rapeseed blanket seedling transplanting and proposed soil environmental parameters suitable for the growth of rapeseed blanket seedlings.

Ensuring efficient and smooth seedling conveying is key to ensuring the efficiency and quality of transplanting. To date, various types of seedling conveying devices with different structures have been proposed worldwide, including single-axis whole-row conveying, double-axis sequential conveying, and electromechanical conveying. Single-axis whole-row conveying was a commonly used method for conveying seedlings, as it had high efficiency. It involved the lateral movement of the seedling picking mechanism to pick up an entire row of seedlings, after which the conveying mechanism moved the seedlings forward in a row. This method reduced the occurrence of misalignment in seedling conveying caused by inertia; however, it necessitates specialized seedling trays, a complex structure, and high costs. Typical examples of machines which used this method included vegetable transplanters developed by companies such as Renaldo in the United States, Ferrari in Italy, and swing transplanters in Japan [9–11]. Moreover, the double-axis sequential conveying mechanism involved coordination between a laterally continuous reciprocating mechanism and a longitudinally intermittent motion mechanism. The seedling picking mechanism only needs to pick up the seedlings at a fixed point. This method was mainly used in rice transplanters. For the electromechanical seedling conveying mechanism, the seedling conveying process was controlled by starting and stopping a DC motor. This method had a simple structure but poor stability, and it was easy to produce cumulative errors, leading to inaccurate seedling conveying [12].

The seedling conveying device of a rapeseed blanket seedling transplanter was divided into two parts: a longitudinal seedling conveying mechanism and a horizontal seedling conveying mechanism; this design offered high efficiency and good stability [13–15]. Before transplanting, the whole seedling blankets were placed on a tilted seedling tray and moved longitudinally via gravity. The horizontal movement of the overall seedling tray was realized by a spatial double-helix cam mechanism. Many reliable design schemes exist that could realize accurate and reliable horizontal seedling conveying [16–18]. The longitudinal seedling conveying mechanism adopted a synchronous belt to realize intermittent movement and drive the seedling blanket's longitudinal motion under the action of friction and gravity. In the design phase, it was recommended to keep the seedling row spacing, the rate of longitudinal seedling conveying, and the rate of longitudinal seedling picking constant. However, because it was impossible to fix the longitudinal position of the seedling blanket relative to the seedling tray, the seedling blanket was compressed under the action of gravity, which led to a reduction in the longitudinal seedling picking rate and the seedling utilization rate in actual testing, resulting in a seedling loss of 5~10%. Furthermore, inconsistency in the number of longitudinal seedlings conveyed and in the seedling row spacing resulted in the seedling needle cutting the seedlings and their roots, seriously affecting the performance of the transplanter as well as the survival, growth, and yield of the seedlings after planting.

In addressing the aforementioned issues, the working principle of the longitudinal seedling conveying mechanism of the rapeseed blanket transplanter was analyzed. Mechanical compression tests were conducted to establish the relationship between compression force and compression amount for rapeseed blankets. A model of the compression of the seedling blanket on the seedling tray was established via force analysis. The main factors affecting the seedling blanket's longitudinal compression and their influence patterns were analyzed through a single-factor test. The structural parameters of the longitudinal seedling conveying mechanism and the mechanical parameters of the seedling blanket were optimized through response surface experimental modelling. The results provide theoretical and empirical support for the optimized design of the seedling conveying mechanism of automatic transplanters and guide the operation of mechanized seedling cultivation using transplanted rapeseed blanket seedlings.

2. Materials and Methods

2.1. Structure and Working Principle

The rapeseed blanket seedling transplanter in this study utilizes a riding-type rice transplanter chassis, as depicted in Figure 1. Its essential components comprise the corrugated disc furrow-opening device, the seedling conveying device, the rotary planting mechanism, and the compacting device [19]. During transplanter operation, the corrugated disc furrow-opening device, powered by hydraulic pressure, creates a seedling furrow in the field with a width of 20 mm and a depth of 30 mm~40 mm. Subsequently, the adjusting wheel is used to maintain the pre-cut furrow, preventing surrounding soil from collapsing into it. As the horizontal seedling conveying mechanism operates, the seedling tray moves continuously sideways, with the seedling needle picking up a seedling block at each interval. Once reaching the end, the longitudinal seedling conveying mechanism activates, moving the entire seedling blanket downward while the horizontal seedling tray begins to move in the opposite direction. Meanwhile, the seedling needle in the planting mechanism cuts a seedling block from the blanket, transports it to the designated position, and plants it into the pre-cut furrow. Finally, the compaction wheel compresses the soil around the furrow, securing the seedlings firmly in place.

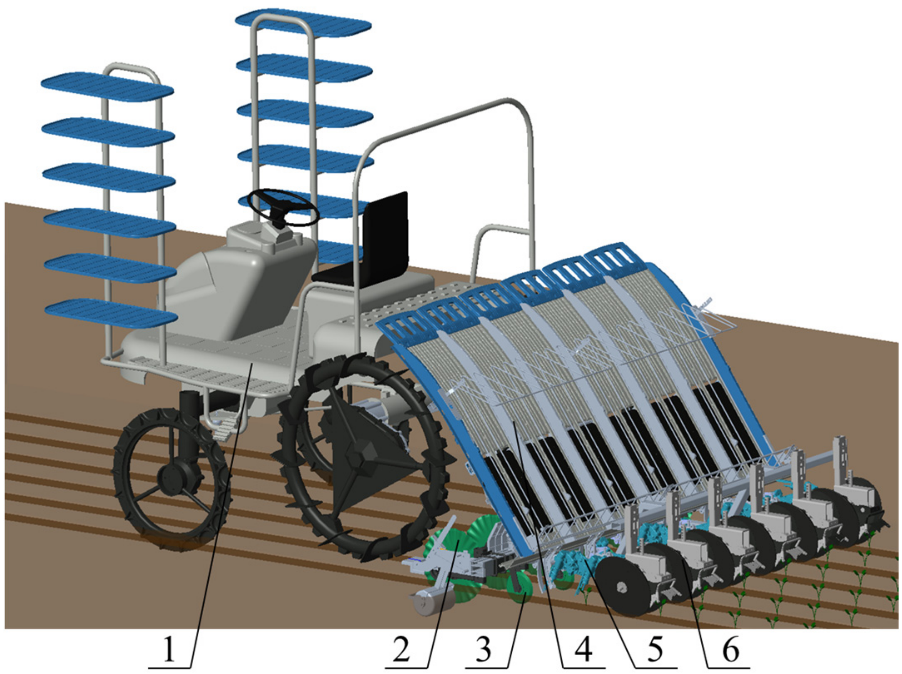

Figure 1. Components of the rapeseed blanket seedling transplanter: (1) riding-type transplanter chassis; (2) furrow-opening device; (3) adjusting wheel; (4) seedling conveying device; (5) planting mechanism; (6) compacting mechanism.

The longitudinal seedling conveying mechanism, depicted in Figure 2, operates conveyor belts affixed to the seedling tray using primary and secondary driven rollers. Two hook-type cams, installed at both ends of the shaft, are located on the back of the seedling trays. During the transplanter's operation, when the seedling tray reaches the laterally extreme positions, the hook-type cam pivots the lifting handle, causing the unidirectional ratchet to rotate to the designed angle, thereby driving the rotation of the seedling conveying belt. During the hook-type cam rotation process, contact with the lifting handle results in separation, forming the maximum rotational angle (θ) for the lifting handle. Moreover, the belt distance is denoted as (S), representing the longitudinal seedling conveying distance, with the calculation given in Equation (1). By designing the position of the hook-type cam relative to the rotational center of the lifting handle and the maximum rotational circle of the hook-type cam, the desired seedling conveying distance is obtained. Increasing the frequency of seedling delivery allows for more seedling blocks to be extracted from a single blanket, but results in smaller and lighter blocks, reducing block cutting and planting quality. Preliminary seedling picking experiments determined the optimal horizontal and longitudinal seedling conveying distances of 23.3 mm and 18 mm, respectively. In addition, a belt roller diameter of 43 mm and a belt thickness of 2 mm were selected, with calculations indicating that the ratchet needs to rotate by 44°.

$$S = \frac{\delta \pi}{360}(D + 2T) \tag{1}$$

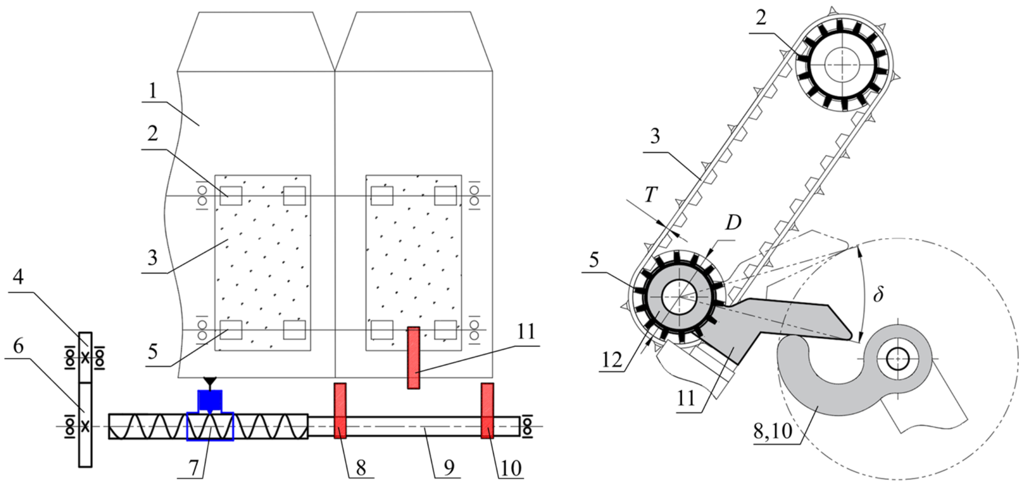

Figure 2. Working principle diagram of longitudinal seedling conveying mechanism: (1) seedling tray; (2) belt-driven roller; (3) seedling conveying belt; (4) driving gear; (5) belt-driven roller; (6) driven gear; (7) horizontal seedling conveying mechanism; (8,10) hook-type cam; (9) longitudinal seedling conveying shaft; (11) lifting handle; (12) unidirectional ratchet; (δ) maximum rotational angle of lifting handle, °; (D) belt roller diameter, mm; (T) belt thickness, mm.

2.2. Compression Analysis of Rapeseed Seedling Blanket

2.2.1. Compression Force Analysis of Seedling Blanket

Before the operation of the rapeseed blanket seedling transplanter, compression deformation occurs in the seedling blanket when placed on the seedling tray. According to actual operating conditions, in which two plates of seedling blankets are placed per row and assuming a uniform mass distribution, force analysis for the seedling blanket is depicted in Figure 3. The compression force for the lower seedling blanket awaiting cutting is obtained through force equilibrium conditions. From Equation (2), it can be deduced that the compression of the seedling blanket is influenced by the seedling blanket's mass, the seedling tray tilt angle, and the friction coefficient between the seedling tray and the seedling blanket.

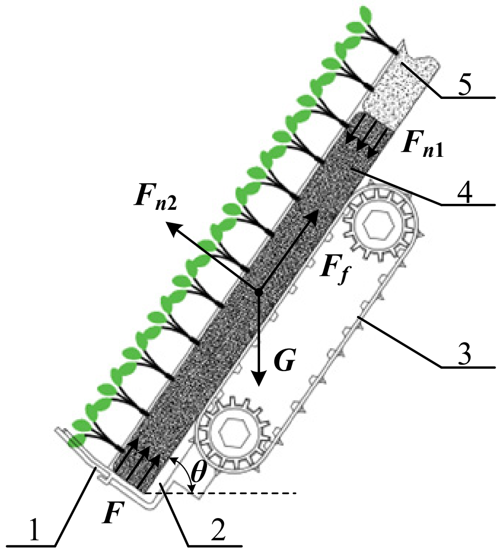

Figure 3. Force analysis of the seedling blankets placed on the seedling tray: (1) retaining plate; (2) seedling tray; (3) seedling conveying belt; (4) lower seedling blanket; (5) upper seedling blanket; (F_{n1}) pressure of the upper seedling blanket on the lower seedling blanket; (F) compression force of lower seedling blanket, N; (F_f) friction force between the seedling blanket and seedling tray, N; (F_{n2}) supporting force of the seedling tray to the seedling blanket, N; (G) seedling blanket gravity, N; (θ) angle of tilted seedling tray, °.

$$\begin{cases} F = F_f - G\sin\theta - F_{n1} \\ F_{n1} = G\sin\theta - Gf_s\cos\theta \\ F_{n2} = G\cos\theta \\ F_f = f_x F_{n2} \end{cases} \tag{2}$$

where F_{n1} (N) is the pressure of the upper seedling blanket on the lower seedling blanket; F_{n2} (N) is the supporting force of the seedling tray to the seedling blanket; F_f (N) is the friction force between the seedling blanket and seedling tray; G (N) is the seedling blanket gravity; f_x is the friction coefficient between the lower seedling blanket and the conveying belt; and f_s is the friction coefficient between the upper seedling blanket and the seedling tray.

2.2.2. Compression Performance Analysis of Seedling Blanket

The rapeseed seedling blanket comprises soil, substrate, and roots, with soil being the primary component. In accordance with the physical properties of the three-phase model of soil, the ratio of the volume of pores and liquid to the volume of solid matter, denoted as the pore ratio, is a compression performance index reflecting the sponginess of the seedling blankets, as depicted in Equation (3); this index is transformed into a parameter expression that can be measured experimentally [20–22]. In addition, the pore ratio before compression (e_0) can be measured through experiments.

$$e = \frac{V_v}{V_s} = \frac{d_s\left(1+\frac{m_w}{m_s}\right)\rho_w}{\frac{m_z}{V_z}} - 1 \tag{3}$$

where V_s (mm^3) is the volume of solid material in the seedling blanket; V_v (mm^3) is the volume of pores and liquid material in the seedling blanket; d_s is the solid relative density of the seedling blanket, denoting the ratio of the solid mass in the seedling blanket to the water mass occupying an equivalent volume, quantified utilizing the relative density bottle method; ρ_w (g/mm^3) is the density of water; m_s (g) is the solid mass in the seedling blanket, measured using the drying method; m_w (g) is the liquid mass in the seedling blanket; m_z is the seedling blanket mass, g; and V_z (mm^3) is the seedling blanket's volume.

Integrating soil compression mechanics theory, the relationship curve between the compression force and the amount of compression on the seedling blanket was established by carrying out a confined compression mechanics test [20]. As illustrated in Figure 4, baffles are present on both sides of the seedling tray. Therefore, it is assumed that the seedlings undergo no lateral deformation under compression during the analysis. The seedling blankets are subjected to a uniformly distributed load, resulting in longitudinal deformation after compression. The following equation can be derived based on the volume relationship before and after the compression of the seedling blanket.

$$\begin{cases} V_0 = h_0 A = V_{v0} + V_{s0} = (1+e_0)V_{s0} \\ V_1 = (h_0 - L(p))A = V_{v1} + V_{s1} = (1+e)V_{s1} \end{cases} \tag{4}$$

where V_0 (mm^3) is the total volume of the seedling blanket before compression, and V_1 (mm^3) is the total volume of the *seedling blanket after compression*.

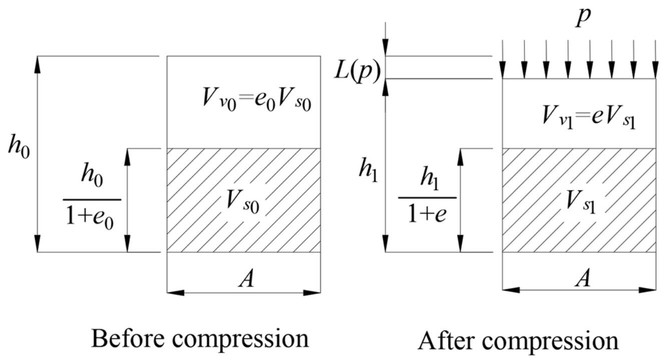

Figure 4. Volume relationship of the seedling blanket before and after compression: (V_{v0}) volume of pores and liquid in a seedling blanket before compression, mm^3; (V_{v1}) volume of pores and liquid in a seedling blanket after compression, mm^3; (V_{s0}) volume of solid matter in a seedling blanket before compression, mm^3; (V_{s1}) volume of solid matter in a seedling blanket after compression, mm^3; (h_0) original length of seedling blanket, mm; (h_1) length of seedling blanket after compression, mm; ($L(p)$) longitudinal compression of seedling blanket, mm; (A) compressed surface area, mm^2; (e) pore ratio; (e_0) pore ratio before compression.

Solid compression is negligible and can be disregarded. Therefore, the volume of solid material within the seedling blanket remains constant before and after compression, that is, $V_{s0} = V_{s1}$. Substituting this into Equations (3) and (4), the relationship between the compression characteristic index e and the amount of compression (L) on the seedling blanket is obtained [20].

$$e = e_0 - \frac{L(p)}{h_0}(1+e_0) \tag{5}$$

Equation (5) [20] reveals two factors influencing the compression amount: the length of the seedling blanket in the compression direction and the pore ratio before and after compression. Subsequently, a confined compression mechanical test was conducted, leveraging the pore ratio index to study the compression performance of the seedling blanket.

2.2.3. Mechanical Compression Test on Seedling Blanket

A mechanical compression test was conducted in October 2023 at the Comprehensive testing laboratory of the Nanjing Agricultural Mechanization Research Institute, which is located at 32.04° N latitude and 118.88° E longitude. According to the technical requirements of rapeseed seedling blankets, seedling trays with dimensions of length 580 mm, width 280 mm, and height 25 mm were used, and rapeseed blanket seedlings of 20 mm thickness and 35 days of age were selected [1]. The rapeseed variety is Ningza 1838. The compression–displacement curves of the seedling blankets were measured and plotted using a universal material testing machine (3343, INSTRON, Norwood, MA, USA, 0~1 kN).

The test conditions are shown in Figure 5. A confined compression test instrument was manufactured according to the requirements of the soil confined compression test, primarily composed of a pressurized piston and a confined compression box with permeable holes. Its dimensions were designed based on the external characteristics of the seedling blankets. Samples of length 70 mm, width 60 mm block-shaped seedling blankets, with smooth surfaces and no seedlings, were placed in the confined compression box. The pressurized piston was aligned to the center of the box and lowered at 40 mm/min; the test was terminated when the displacement reached 40 mm.

Figure 5. Test conditions for seedling blanket compression test.

The moisture content of the seedling blankets ranged from 50% to 80% and was included as a test factor, with tests on each group being repeated five times. This resulted in four curves mapping the relationships between the compressive force and the amount of compression, as shown in Figure 6. Substituting the test data into Equation (5), the *e*–*p* curves of the seedling blankets were solved and fitted using the rational fitting method in MATLAB R2015b, with the numerator set at a degree of 2 and the denominator set at a degree of 1. The fitting equations of the *e*–*p* curves at various moisture contents were obtained, as shown in Equation (6), and the correlation coefficients R^2 ranged from 0.9997 to 1. The *e*–*p* curves effectively illustrate the compressive mechanical characteristics of the seedling blankets [20,23]. As illustrated in Figure 7, it is evident that a reduction in the moisture content leads to an increased steepness of the compression curve, signifying the heightened compressibility of the seedling blanket. This variation in compressive performance among seedling blankets with different moisture contents is especially prominent in the pressure range below 0.02 MPa. To mitigate seedling compression, increasing the moisture content and reducing pressure prove advantageous.

$$\begin{cases} e_{50} = \left(-160.2p^2 + 14.59p + 0.06106\right)/(p + 0.00334) \\ e_{60} = \left(-112.6p^2 + 11.14p + 0.005588\right)/(p + 0.0004693) \\ e_{70} = \left(-62.4p^2 + 6.538p + 0.01784\right)/(p + 0.002453) \\ e_{80} = \left(-36.18p^2 + 3.457p + 0.007862\right)/(p + 0.002053) \end{cases} \tag{6}$$

where e_{50} is the pore ratio of the seedling blanket with a 50% moisture content; e_{60} is the pore ratio of the seedling blanket with a 60% moisture content; e_{70} is the pore ratio of the seedling blanket with a 70% moisture content; e_{80} is the pore ratio of the seedling blanket with an 80% moisture content; and p (MPa) is compressive pressure.

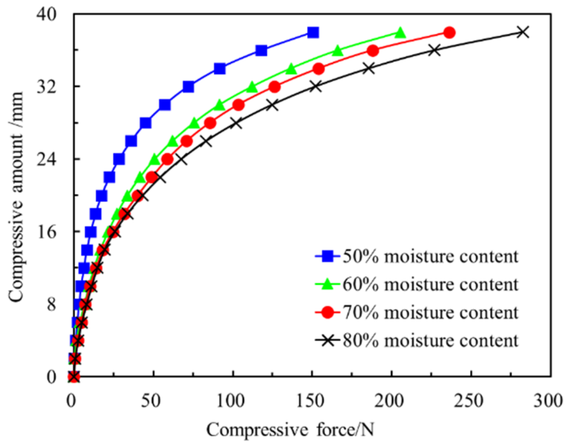

Figure 6. Relationship curves of compressive force and amount of compression for the seedling blankets.

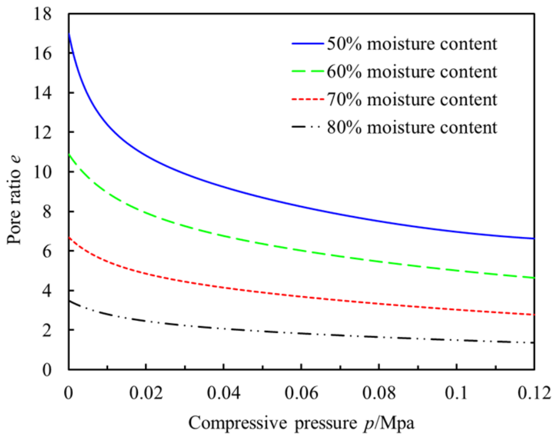

Figure 7. *e*–*p* curves of seedling blankets with different moisture contents.

2.2.4. Compression Equation and Single-Factor Test

Combining Equations (2), (5) and (6), Equation (7) was established, which describes the amount of compression on the seedling blanket placed on the seedling tray. The amount of compression of the seedling blanket is primarily influenced by the mass, moisture content, and internal composition of the seedling blanket as well as the seedling tray tilt angle and the friction coefficient between the seedling tray and seedling blanket [24,25]. In standardized seedling cultivation, seedling blankets are assumed to have similar internal composition characteristics. The friction coefficient between the seedling tray and seedling blanket is material-dependent. A smaller friction coefficient results in a lower friction force and greater compression of the seedling blanket, making it prone to slipping during longitudinal conveying. However, excessively high friction coefficients impede the downward sliding of the seedling blankets during the placement process, causing potential damage to the blanket and impacting operational efficiency. Using the materials of the rice transplanter seedling tray, the average friction coefficient of the contact between the seedling plate and the conveyor belt was measured to be 0.8, while the average friction coefficient with the plastic parts of the seedling blanket tray was 0.7, determined through the slope test. Using standard-sized seedling trays for cultivation, the mass of the seedling blanket was influenced by the moisture content and the thickness.

$$\begin{aligned} L_{mi} &= \frac{e_{0i} - e_i(p_m)}{1 + e_{0i}} h_m \qquad i = 50, 60, 70, 80 \\ p_m &= \frac{m_m}{A_m} \times (0.02 \sin\theta - \cos\theta (f_x + f_s)) \end{aligned} \tag{7}$$

where L_{mi} (mm) is the amount of seedling blanket compression at different moisture contents, mm; e_{0i} is the initial pore ratio of the seedling blankets at different moisture contents; $e_i(p_m)$ is the e–p fitting curve equation for seedling blankets at different moisture contents; p_m (MPa) is the pressure of the seedling blanket placed on the seedling tray; and i represents the moisture content.

Equation (7) was used to obtain the relationship curves between the seedling blanket moisture content, the seedling blanket thickness, and the tray tilt angle. The analytical results are shown in Figure 8. Adjusting the influencing factors within the set range obtains a variation in the amount of seedling blanket compression between 1 and 48 mm, indicating a highly significant influence. Reducing the seedling tray tilt angle, maintaining a moisture content of around 70%, or increasing the seedling blanket thickness can decrease the compression of the rapeseed seedling blanket.

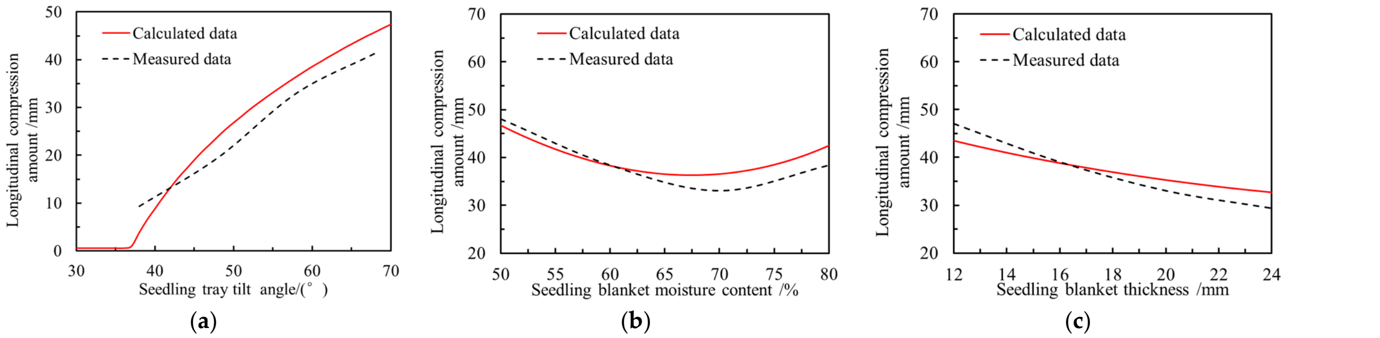

Figure 8. The relationship curve between key factors and seedling blanket compression amount. (**a**) Relationship between seedling tray tilt angle and compression amount; (**b**) Relationship between seedling blanket moisture content and compression amount; (**c**) Relationship between seedling blanket thickness and compression amount.

Single-factor tests were conducted to prove the theoretical results. The test scheme is shown in Table 1. The seedling tray tilt angle of the rice transplanter is typically between 50° and 60° [26]. The rapeseed blanket seedling transplanter studied here has a tray tilt angle designed at 58°. Therefore, the experimental range for the tray tilt angle was set to 38~68°. The saturated moisture content of the rapeseed seedling blanket was approximately 83%; thus, the moisture content range was set to 50~80%. A seedling blanket with a thickness below 12 mm cannot form a blanket, so considering a tray height of 25 mm and the increase in cultivation cost with the increase in seedling blanket thickness, the range for seedling blanket thickness was set at 12 mm~24 mm.

Table 1. Factors and levels of the single-factor test.

Levels	Seedling Tray Tilt Angle, °	Seedling Blanket Moisture Content, %	Seedling Blanket Thickness, mm
1	38	50	12
2	48	60	16
3 (counter level)	58	70	20
4	68	80	24

The different rapeseed blanket seedling thicknesses used for the tests are shown in Figure 8. Initially, a drying test was conducted to obtain the dry mass of seedling blankets with different thicknesses using an electric moisture meter (LC-DHS-20A, LICHEN, Jinjiang, China; 0~110 g; measurement accuracy, 0.001 g). The relationship between the seedling blanket thickness (t) and dry mass (m_f) was fitted using a third-degree polynomial equation: $m_f = 0.026t^3 - 1.625t^2 + 42.833t + 39$. Subsequently, Equation (8) was employed to calculate the total mass of the rapeseed seedling blanket with varying moisture contents. The relationship between the thickness, moisture content, and mass of the rapeseed seedling blankets is shown in Figure 9. Utilizing the electric moisture meter and employing the weighing method, other seedling blankets were adjusted to four different moisture content levels: 50%, 60%, 70%, and 80%, with an error controlled within ±1.5%. The process of the test is to measure the length of the seedling blanket after being placed on the seedling tray. To facilitate a better comparison with the test results, the calculated amounts of seedling blanket compression for different seedling tray tilt angles, moisture contents, and thicknesses were plotted alongside the measured test data, as illustrated in Figure 10.

$$m_{mi} = \frac{m_{fi}}{1-\eta_i} + m_y \qquad i = 50,\ 60,\ 70,\ 80 \tag{8}$$

where m_{mi} (g) is the total mass of the rapeseed seedling blanket at different moisture contents; m_{fi} (g) is the dry mass of the seedling blanket; η_i is the moisture content; and m_y (g) is the mass of the seedlings, where the total mass of seedlings with a height of 80 mm is measured as approximately 325 g.

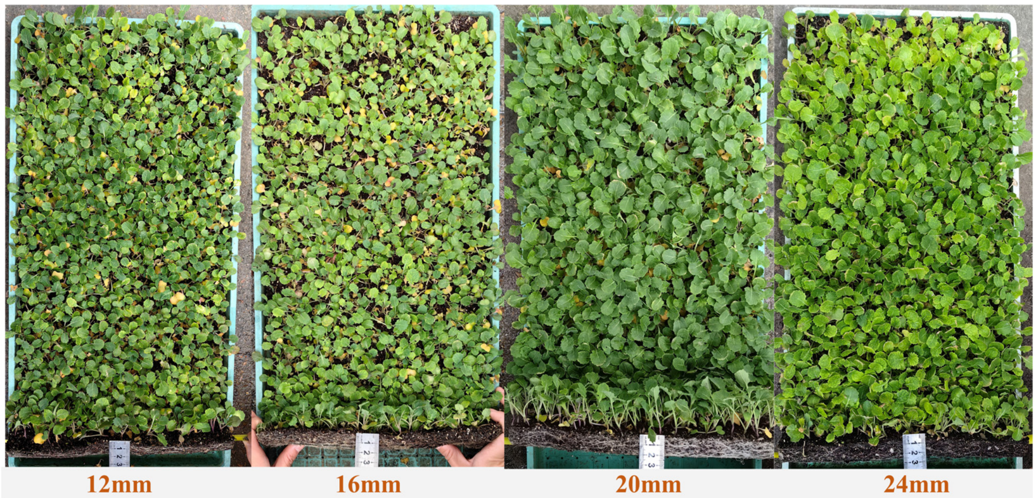

Figure 9. Different thicknesses of rapeseed seedling blankets.

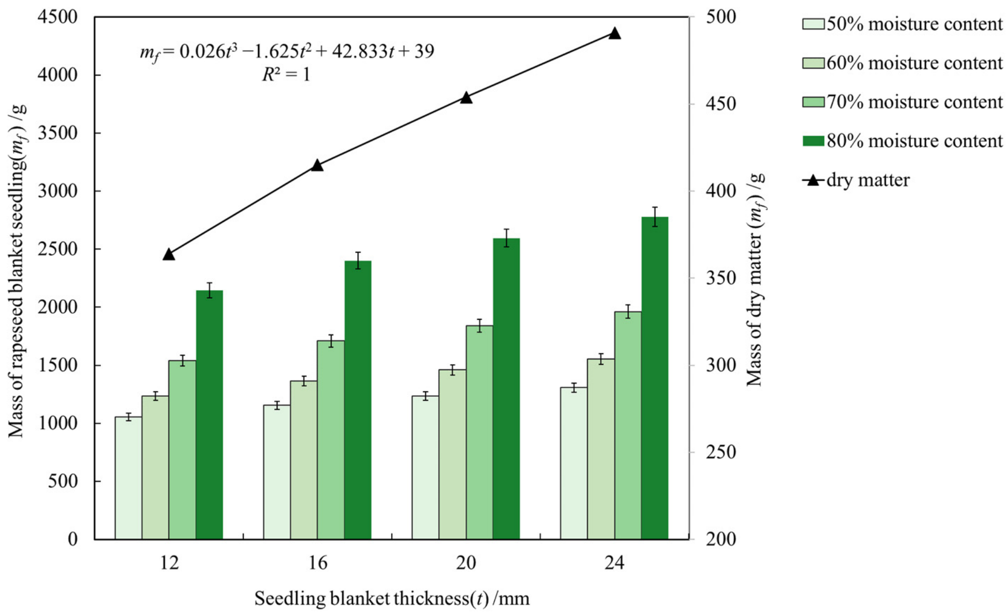

Figure 10. Relationship of thickness, moisture content, and mass for rapeseed seedling blankets.

The results indicate a high degree of agreement between the calculated and measured values. Specifically, the following results were found: (1) At a seedling tray tilt angle of 38°, the calculated seedling blanket compression amount was minimal, with a value of 3.9 mm, compared to the test value of 9.33 mm, yielding a discrepancy of 4.9 mm. (2) For a seedling blanket moisture content of 70%, the calculated compression amount reached the minimum value of 36.52 mm, while the test value was 33.00 mm, resulting in a relative error of 3.52 mm. (3) At a seedling blanket thickness of 24 mm, the calculated compression was least at 32.71 mm, compared to the test value of 29.33 mm, leading to a relative error of 3.38 mm. In summary, the compression mathematical model, as established in this study, aptly mirrors the longitudinal compression when the seedling blanket is positioned on the seedling tray. This provides a solid theoretical foundation for subsequent optimizations.

2.3. Parameter Optimization Test

Based on the seedling compression theory and analytical tests, placing seedling blankets on the seedling tray induces longitudinal compression, resulting in reduced seedling blanket length, inaccurate longitudinal seedling conveying, and fragmentation or damage to the seedling blanket. Therefore, to minimize the compression of the seedling blanket, ensure consistency in the longitudinal seedling delivery, and enhance the qualified-block-cutting rate, the Box–Behnken experimental method was employed to optimize the seedling tray tilt angle, seedling blanket moisture content, and seedling blanket thickness [27–29]. The optimal combination of the seedling blanket's mechanical characteristics and the mechanism parameters of the seedling tray was obtained. Subsequently, the actual inter-row spacing of the seedlings was introduced based on the optimized initial compression, and the longitudinal seedling conveying and seedling extraction were adjusted to improve the pick-up accuracy of the seedlings.

The Box–Behnken method is utilized to design a set of experiments, using a quadratic polynomial model to approximate the effects of multiple factors on system responses, and to determine the optimal combination of factors. The quadratic polynomial model assumed by the Box–Behnken method is [30]:

$$Y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i<j}^{k} \beta_{ij} x_i x_j + \epsilon \tag{9}$$

where Y is the response variable of the system; x_i is the level of the ith factor; β_0 is the constant term; β_i is the main effect coefficient of the ith factor; β_{ii} is the quadratic effect coefficient of the ith factor; β_{ij} is the interaction effect coefficient between the ith and jth factors; ϵ is the error term.

The Box–Behnken method designs experimental points at midpoints of the edges of the experimental space, and it requires a minimum of three continuous factors, thereby reducing the number of experiments. To fit the model using least squares, we represent the model as a matrix form:

$$Y = X\beta + \epsilon \tag{10}$$

where X is the experimental design matrix; β is the coefficient matrix; ϵ is the error term matrix.

Using the least squares method to solve for the parameter estimates $\hat{\beta}$:

$$\hat{\beta} = \left(X^T X\right)^{-1} X^T Y \tag{11}$$

Substituting the parameter estimates into the model to obtain the fitted response surface model:

$$\hat{Y} = X\hat{\beta} \tag{12}$$

The response surface model is optimized to find the optimal level combination of factors that make the maximum or minimum response:

$$\hat{x}_{\text{opt}} = \text{argmax}\left(\hat{Y}\right) \tag{13}$$

$$\hat{x}_{\text{opt}} = \operatorname{argmin}(\hat{Y}) \tag{14}$$

By building a quadratic polynomial model, designing an experimental matrix, model fitting, and optimization analysis, the Box–Behnken method can effectively explore and optimize the response of a multi-factor system with a small number of experiments.

2.3.1. Test Conditions

Seedling cultivation was performed in November 2023. The test site was located in the National Machinery Heavy Industry (Changzhou) Excavator Co., Ltd. (Changzhou, China) agricultural machinery production technology center (32.03° N latitude and 120.01° E longitude). According to the test, rapeseed blanket seedlings with different seedling blanket thicknesses of 16 mm, 20 mm, and 24 mm were cultivated. The age of the seedlings was 35 days. The number of seedlings per tray was about 500 plants, the seedlings were not scattered with both hands, and the average seedling height was 82 mm, reaching the requirements to start the machine planting test.

2.3.2. Test Method

The following requirements of the transplanter were satisfied when picking the seedlings: (1) minimize the compression of the seedling blanket; (2) during longitudinal seedling conveying, ensure consistency in the seedling conveying distance, the seedling row spacing, and the longitudinal block-cutting width, avoiding occurrences of secondary compression or slipping; and (3) guarantee the integrity of the seedling block. There should be no substrate block fragmentation. As a result, the longitudinal compression, coefficient of variation in seedling conveying distance, and qualified-block-cutting rate were defined as indices.

- Compression amount

The amount of longitudinal compression of the seedling blanket (Y_1) is obtained by subtracting the standard length before compression from the compressed length of the seedling blanket after it is placed on the seedling tray, using a tape measure (0~5 m; measurement accuracy, 1 mm).

- Coefficient of variation in seedling conveying distance

After a row of seedlings is completely planted, the seedling blanket moves downward. The position of the upper edge of the seedling blanket is marked on the side of the seedling tray to measure the longitudinal movement of the seedling blanket (S_m). The theoretical longitudinal seedling distance (S_p) for this experiment is 18 mm. The coefficient of variation in the seedling conveying distance (Y_2) is calculated using Equation (9).

$$\begin{cases} Y_2 = \dfrac{\sqrt{\frac{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)}{n}}}{\bar{x}} \\ x_i = \left|S_p - S_{mi}\right| \end{cases} \tag{15}$$

where x_i (mm) is the deviation in the longitudinal seedling conveying distance; S_p (mm) is the theoretical longitudinal seedling conveying distance; S_{mi} (mm) is the longitudinal movement distance of the seedling blanket; and n is the longitudinal seedling picking time of a seedling blanket plate.

- Qualified-block-cutting rate

A theoretical size of the cut-off seedling block is obtained according to the cutting parameter. If the mass loss of the seedling block is less than 20%, the block is considered qualified [31]. The qualified-block-cutting rate is the proportion of the number of unfragmented seedling blocks, which is calculated by Equation (16).

$$Y_3 = \frac{N_c}{N} \times 100\% \tag{16}$$

where N_c is the number of unfragmented seedling blocks, and N is the total number of test samples for each group.

The value range selected for each factor was based on the results from the single-factor tests. The factors and their levels are shown in Table 2. The adjustment method for each parameter is the same as in the single-factor tests. After measuring the compression of the seedling blanket, block-cutting and seedling-picking tests were conducted. The experimental procedure involved recording the longitudinal displacement of the seedling blanket on the seedling tray, collecting the cut seedling blocks, stopping the test once an entire seedling blanket plate was cut, and then recording the distance of the longitudinal movement of the seedling blanket and the number of qualified blocks, using Equations (15) and (16) to calculate all indices. The test site is shown in Figure 11. Several group tests were performed, with each test repeated three times.

Table 2. Factors and levels of response surface tests.

Factor Level	Seedling Tray Tilt Angle, A (°)	Seedling Blanket Moisture Content, B (%)	Seedling Blanket Thickness, C (mm)
−1	48	65	16
0	53	70	20
1	58	75	24

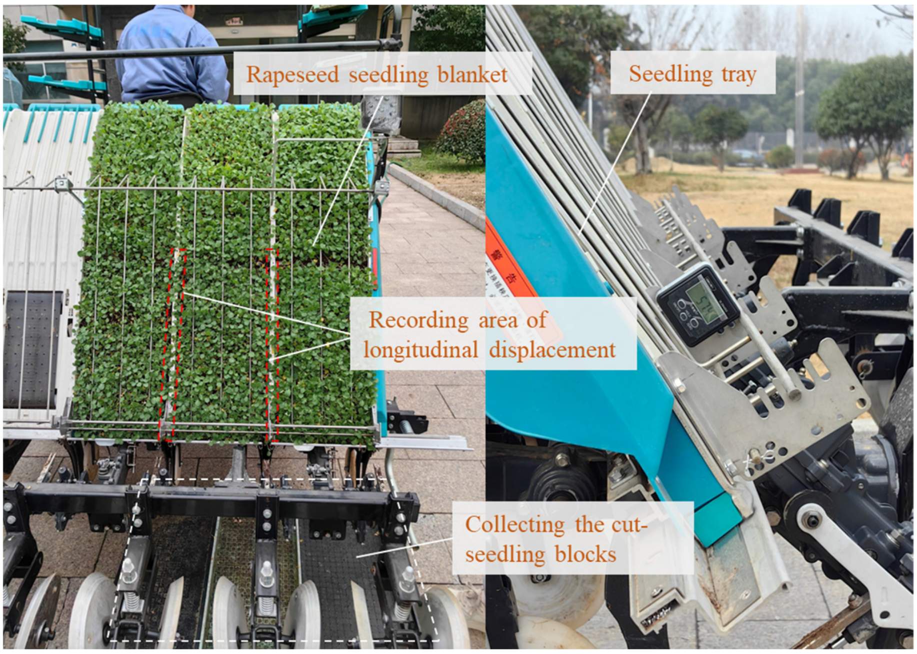

Figure 11. Test equipment and site.

3. Results

3.1. Test Results and Analysis

In order to establish the optimization model of longitudinal seedling conveying parameters of the rapeseed blanket transplanter, analyze the important factors and interactions affecting the performance of longitudinal seedling conveying, and optimize the best combination conditions of multiple factors affecting the reaction [32,33]. The parameter optimization test scheme for the seedbed preparation machine was designed according to the results of Box–Behnken response surface tests performed with three factors and three levels. The specifics of the test schemes and the obtained test data results are shown in Table 3.

Table 3. Test scheme and results of transplanter parameter optimization tests.

Number	A/(°)	B/(%)	C/(mm)	Y_1/mm	Y_2	Y_3/%	Comprehensive Scores D_v
1	−1	−1	0	22.67	2.99	77.8	53.79
2	−1	0	−1	20.67	3.65	71.1	41.14
3	−1	0	1	16.33	2.05	82.8	87.84
4	−1	1	0	19.33	2.48	85.3	74.84
5	0	−1	−1	33	3.04	60.3	21.63
6	0	−1	1	27	2.8	80.1	50.01
7	0	0	0	22	1.79	88.1	84.44
8	0	0	0	23.33	1.79	88.6	82.02
9	0	0	0	22	1.83	89	84.18
10	0	0	0	23	1.89	88.1	80.46
11	0	0	0	22.67	1.78	87.4	82.86
12	0	1	−1	32	2.45	76.2	44.37
13	0	1	1	24	2.05	89.9	76.37
14	1	−1	0	32.33	3.71	78.2	20.39
15	1	0	−1	36	3.25	67.9	15.87
16	1	0	1	27.67	3.84	90.2	34.32
17	1	1	0	34	2.94	94.7	41.54

Based on the data in Table 3, Design-Expert 13 software was used to conduct multiple regression fitting and thereby determine the optimal operation parameters. A second-order polynomial response surface regression model was established between the three independent variables. The significance values obtained from this regression analysis are listed in Table 4. According to these results, a response surface diagram was obtained describing the influences of the interactions between each independent variable on the response variable, as shown in Figure 12.

From Table 4, it can be observed that for the compression model, the coefficient of variation in the seedling conveying distance model, and the qualified-block-cutting rate model, a value of $p < 0.0001$ indicates a high significance; for the lack-of-fit analysis, values of $p > 0.05$ indicate that the regression equation had a high degree of fit. Therefore, the compression model, the coefficient of variation in the seedling conveying distance model, and the qualified-block-cutting rate model can be used to optimize the structural parameters of the seedling tray and the mechanical parameters of the rapeseed seedling blanket.

Table 4. Significance test results.

Source	Y_1				Y_2			
	Sum of Squares	df	F	p-Value	Sum of Squares	df	F	p-Value
Model	529.63	9	137.22	<0.0001	3.77	9	210.26	<0.0001
A	325.13	1	758.13	<0.0001 **	0.37	1	184.08	<0.0001 **
B	4.02	1	9.37	0.0183 *	0.38	1	191.32	<0.0001 **
C	88.91	1	207.32	<0.0001 **	0.15	1	75.88	<0.0001 **
AB	6.28	1	14.63	0.0065 *	0.01	1	3.77	0.0934
AC	3.98	1	9.28	0.0187 *	0.53	1	267.34	<0.0001 **
BC	1	1	2.33	0.1706	0.00	1	1.43	0.2712
A^2	0.4447	1	1.04	0.3424	1.56	1	782.98	<0.0001 **
B^2	72.78	1	169.7	<0.0001 **	0.17	1	84.92	<0.0001 **
C^2	21.17	1	49.37	0.0002 **	0.41	1	205.84	<0.0001 **
Residual	3	7			0.01	7		
Lack of fit	1.58	3	1.49	0.3451	0.01	3	3.7	0.1194
Pure Error	1.42	4			0.00	4		
Cor Total	532.63	16			3.79	16		

Table 4. *Cont.*

Source	Y_3				D_v			
	Sum of Squares	df	F	p-Value	Sum of Squares	df	F	p-Value
Model	1262.65	9	138.04	<0.0001	10,446.69	9	215.37	<0.0001
A	12.5	1	12.3	0.0099 *	2645.36	1	490.82	<0.0001 **
B	284.41	1	279.83	<0.0001 **	1041.95	1	193.32	<0.0001 **
C	504.03	1	495.92	<0.0001 **	1969.34	1	365.39	<0.0001 **
AB	12.25	1	12.05	0.0104 *	0.0022	1	0.0004	0.9846
AC	18.49	1	18.19	0.0037 *	199.48	1	37.01	0.0005 **
BC	9.3	1	9.15	0.0192 *	3.29	1	0.6103	0.4603
A^2	11.92	1	11.73	0.0111 *	1556.5	1	288.79	<0.0001 **
B^2	39.36	1	38.73	0.0004 **	1068.02	1	198.16	<0.0001 **
C^2	345.42	1	339.87	<0.0001 **	1483.92	1	275.33	<0.0001 **
Residual	7.11	7			37.73	7		
Lack of fit	5.66	3	5.2	0.0726	27.06	3	3.38	0.135
Pure Error	1.45	4			10.67	4		
Cor Total	1269.76	16			10,484.41	16		

Note: $p \leq 0.001$, highly significant **; $p \leq 0.05$, significant *; $p > 0.1$ not significant.

In compression model Y_1, three of the regression variables, namely A, C, and B^2 and C^2, were highly significant ($p < 0.001$), and variables B, AB, and AC were significant ($p < 0.05$); none of the remaining conditions were significant. In model Y_2 concerning the coefficient of variation in seedling conveying distance, three regression variables (namely A, B, and C; AC; and A^2, B^2, and C^2) were highly significant ($p < 0.001$); none of the remaining conditions were significant. In the qualified-block-cutting rate model Y_3, three regression variables, namely B, C, and B^2 and C^2, were highly significant ($p < 0.001$), and variables A, AB, AC, BC, and A^2 were significant ($p < 0.05$); none of the remaining conditions were significant.

The test results indicated that both excessively high and low moisture contents and seedling blanket thicknesses increased the longitudinal compression of the seedling blanket [34]. A higher seedling tray tilt angle significantly increased the longitudinal compression and notably enhanced the change trends of both the seedling blanket moisture content and the seedling blanket thickness. In the case of a seedling tray with a steep tilt angle, the thicker seedling blanket was significantly affected by secondary compression, leading to reduced consistency in longitudinal seedling conveying. In the case of a seedling tray with a flat tilt angle, the thinner seedling blanket was prone to slipping against the belt, resulting in reduced and inconsistent seedling conveying distances. Moreover, higher moisture content and thicker seedling blankets exhibited increased resistance to fragmentation when cutting the seedling blocks, thereby enhancing the block-cutting effectiveness of the planting mechanism [35]. An excessive seedling blanket thickness increased the soil content within the seedling blanket and diminished root twine performance, slightly reducing the qualified-block-cutting rate. In comparison, the influence of the seedling tray's tilt angle on the qualified-block-cutting rate was slightly lower. However, when the seedling tray tilt angle was excessively large, the thinner seedling blanket tended to bend and curl during longitudinal seedling conveying, decreasing the block-cutting performance.

Therefore, this study obtained the following regression equations for models Y_1, Y_2, and Y_3 by neglecting non-significant regression variables:

$$\begin{aligned} Y_1 &= 22.6 + 6.38A - 0.7087B - 3.33C + 1.25AB - 0.9975AC + 4.16B^2 + 2.24C^2 \\ Y_2 &= 1.21 + 0.2142A - 0.2183B - 0.1375C + 0.0433AC + 0.6088A^2 + 0.2005B^2 + 0.3122C^2 \\ Y_3 &= 88.24 + 1.25A + 5.96B + 7.94C + 1.75AB + 2.15AC - 1.52BC - 1.68A^2 - 3.06B^2 - 9.06C^2 \end{aligned} \tag{17}$$

Given the inherent contradictions among the three indicators, a comprehensive scoring approach was employed in this study to determine the optimal solution. Prior to calculating the comprehensive score, the indicators were normalized [36].

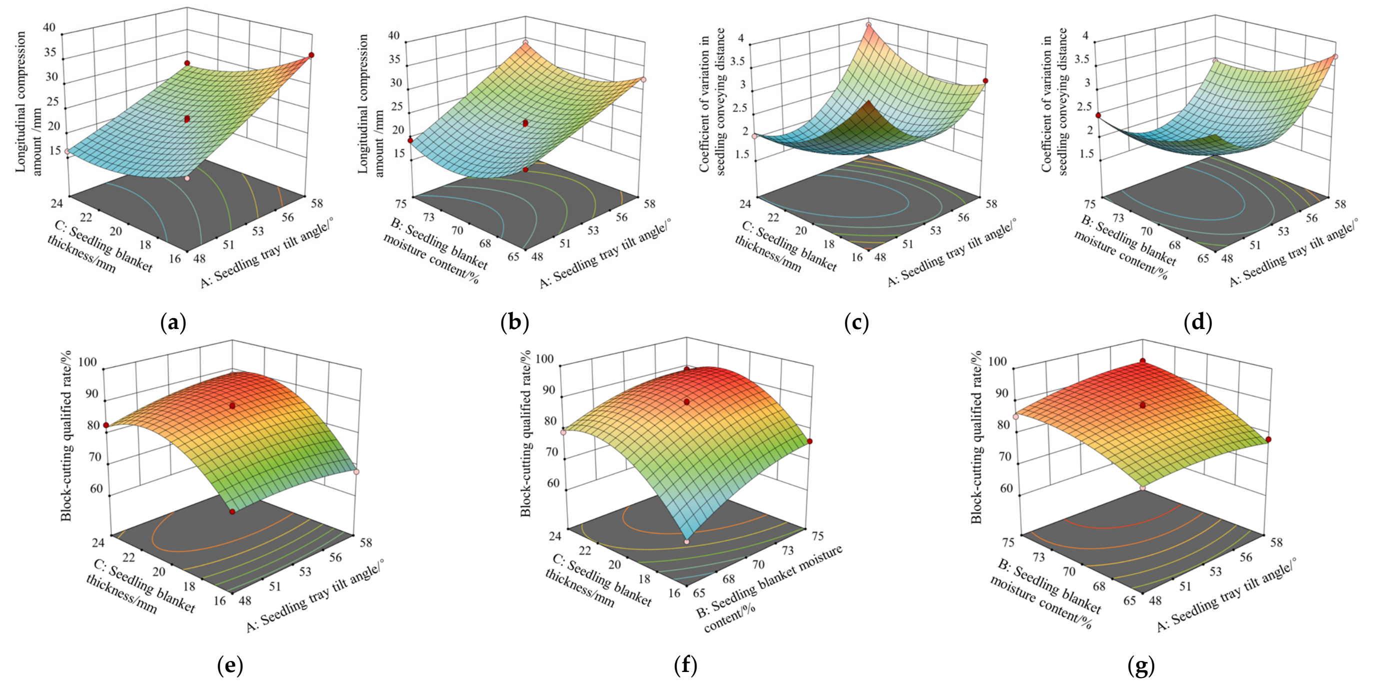

Figure 12. Influence of factors on indices. (**a**) Influence of seedling blanket thickness and seedling tray tilt angle on longitudinal compression; (**b**) influence of seedling blanket moisture content and seedling tray tilt angle on longitudinal compression; (**c**) influence of seedling blanket thickness and seedling tray tilt angle on the coefficient of variation in longitudinal seedling conveying distance; (**d**) influence of seedling blanket moisture content and seedling tray tilt angle on coefficient of variation in longitudinal seedling conveying distance; (**e**) influence of seedling blanket thickness and seedling tray tilt angle on qualified-block-cutting rate; (**f**) influence of seedling blanket thickness and seedling blanket moisture content on qualified-block-cutting rate; (**g**) influence of seedling blanket moisture content and seedling tray tilt angle on qualified-block-cutting rate.

The normalized equations used to achieve the minimum allowable compression and the minimum coefficient of variation in seedling conveying distance are as follows:

$$d_{Y1-i} = \frac{Y_{1\max} - Y_{1i}}{Y_{1\max} - Y_{1\min}} \tag{18}$$

$$d_{Y2-i} = \frac{Y_{2\max} - Y_{2i}}{Y_{2\max} - Y_{2\min}} \tag{19}$$

where d_{Y1-i} is the normalized value of the maximum longitudinal compression allowed in each group of tests; $Y_{1\max}$ (mm) is the maximum longitudinal compression allowed in the tests; $Y_{1\min}$ (mm) is the minimum longitudinal compression in the tests; Y_{1i} (mm) is the test value of the compression in each group of tests; d_{Y2-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 normalized equation for achieving the maximum allowable qualified-block-cutting rate is as follows:

$$d_{Y3-i} = \frac{Y_{3\max} - Y_{3i}}{Y_{3\max} - Y_{3\min}} \tag{20}$$

where d_{Y3-i} is the normalized value of the minimum qualified-block-cutting rate allowed in each group of tests; $Y_{3\max}$ (%) is the maximum value of the qualified-block-cutting rate in the tests; $Y_{3\min}$ (%) 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 mechanisms 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:

$$D_{v-i} = (0.4d_{Y1-i} + 0.4d_{Y2-i} + 0.2d_{Y3-i}) \times 100 \tag{21}$$

The results of the weighted comprehensive score index (D_v) calculated using Equation (15) are listed in Table 3. Variance analysis was performed on the indicators of the comprehensive score test, and the results are listed in Table 4. The *p*-value of the comprehensive score model is less than 0.0001, which indicates a high significance, and the lack-of-fit values are more than 0.05, which indicates that the regression equation had a high degree of fit.

The comprehensive score model is optimized using Design-Expert 13 software. The optimization results show that the predicted optimal parameters were a seedling tray tilt angle of 50.14°, a seedling blanket moisture content of 71.86%, and a seedling blanket thickness of 22.13 mm; using these parameters, the transplanter achieved a comprehensive score of 94.3, a longitudinal compression of 18.17 mm, a coefficient of variation in longitudinal seedling conveying distance of 1.142, and a qualified-block-cutting rate of 90%. The operation quality indicators obtained conform to pertinent technical criteria in the technical standards of the dryland transplanter industry and agronomic production requirements, illustrating that the seedling conveying and block-cutting performance using the optimized parameters achieved superior working performance.

3.2. Field Verification Test

After adjusting the seedling tray tilt angle, cultivating the rapeseed blanket seedlings with a thickness of 22 mm, and regulating the moisture content to 71.86% within an allowable range of ±1.5%, a field test verification was conducted, as shown in Figure 13. The field tests were repeated three times using the optimized results, and the results were averaged. Finally, the longitudinal compression was 16.67 mm, the coefficient of variation in the longitudinal seedling conveying distance was 1.41, and the qualified-block-cutting rate was 92.2%.

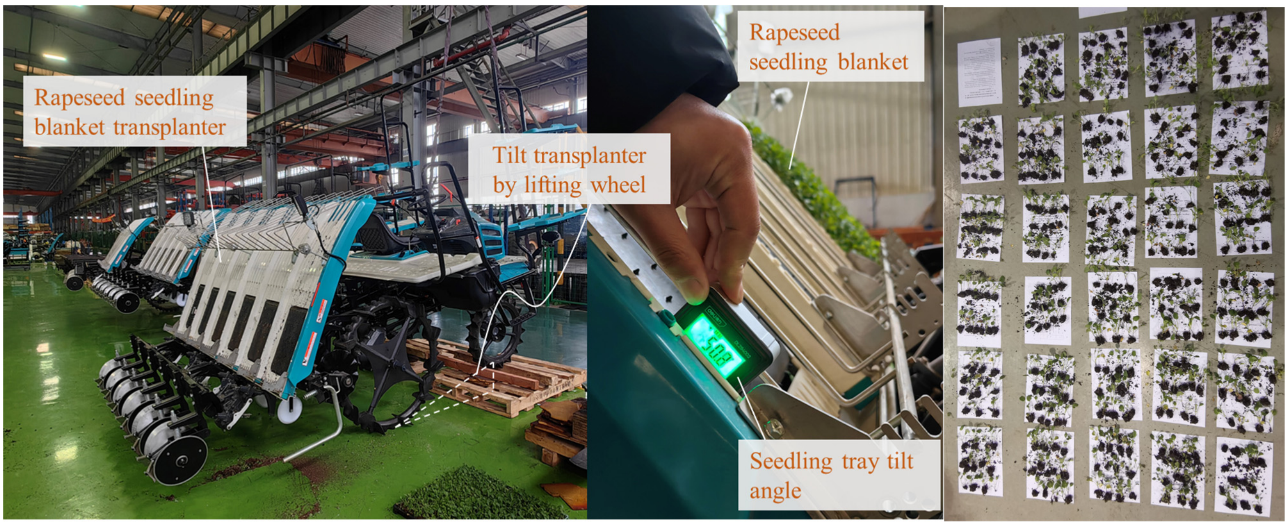

Figure 13. Verification test site.

The relative discrepancies between the experimental and predicted values of longitudinal compression, the coefficient of variation in the longitudinal seedling conveying distance, and the qualified-block-cutting rate are negligible, signifying a judicious selection of optimization conditions. Consequently, the optimized parameters result in a high-performance operation that adheres to standards for field application.

In previous experiments, the longitudinal compression of seedling blocks during the operation of the rapeseed blanket seedling transplanter ranged from 25 mm to 55 mm. Following optimization, the longitudinal compression of the seedling blocks decreased to 16.67 mm, representing a reduction of 33.3% to 70%. Based on the optimized results, the compressed length of the seedling blanket was 563.3 mm, with a calculated inter-row spacing of 17 mm for 33 rows. The longitudinal block-cutting width of the machine was adjusted accordingly. A comparative block-cutting test was conducted before and after the adjustment of the seedling conveying parameters. The results are presented in Table 5. An increase of 24 seedling blocks per plate was observed compared to the previous configuration. The empty seedling rate decreased to 2.5%, demonstrating a decrease of 4.24 percentage points, while the proportion of seedling blocks containing 1~2 seedlings (qualified seedling picking rate) increased to 93.4%, denoting an increase of 6.75 percentage points.

Table 5. Comparative tests of the block-cutting effect.

Test Result	Longitudinal Block-Cutting Width	Number of Rows in Block Cutting	Number of Cut Blocks Per Plate	Empty Seedling Rate, %	Qualified Seedling Picking Rate, %
1	17 mm	33	396	4.0	93.4%
2	18 mm	31	372	8.3	87.0%

In comparison to the prior test, the amount of longitudinal compression was noticeably diminished, and the transplanter's uniform longitudinal seedling conveying and low-loss block-cutting performance were significantly enhanced. This study therefore provides a reference for rapeseed blanket seedling parameters suitable for mechanical transplanting processes. Reducing the longitudinal compression of the seedling blankets can enhance the utilization rate of each seedling blanket plate and reduce transplanting operation costs. Precise longitudinal seedling conveying can reduce the frequency of the main root neck of the seedlings being cut by seedling needles, thereby helping to improve the survival rate of seedlings after transplanting.

4. Discussion

Optimizing the automatic seedling conveying performance and seedling picking quality of an automatic transplanter is key to improving transplanter performance. This study conducted experimental optimization of the mechanical parameters of seedling blankets and the structural parameters of seedling trays based on theoretical analysis. Good optimization results were achieved, reducing the longitudinal compression of the seedling blanket, improving the accuracy of the longitudinal seedling delivery, and enhancing the block-cutting quality. This study provides a set of parameters suitable for the mechanical transplanting of rapeseed blanket seedlings in the rapeseed production process. In addition, reducing the longitudinal compression of the rapeseed blanket and enhancing the longitudinal precision of seedling conveying can improve the utilization rate of the rapeseed blanket, thereby reducing transplanting costs and also enhancing the survival rate of seedlings after transplanting. Additionally, the design of the longitudinal seedling conveying mechanism and its delivery methods can be further optimized, such as by cultivating seedling blankets with convex–concave-shaped bottoms and designing conveyor belts that engage with the bottoms of the seedling blankets to limit longitudinal compression. Another approach involves designing a clamping device for the upper part of the seedling blanket. Finally, it should be ensured that the design of these mechanisms does not complicate the seedling placement process nor affect the seedling placement efficiency, which is a notable challenge and a key focus of further research.

5. Conclusions

This study addressed the issues of longitudinal seedling compression, high empty seedling rates, poor block-cutting quality, and low qualified seedling picking rate during the operation of rapeseed blanket seedling transplanters. First, mechanical tests were conducted to obtain the mechanical curve of the longitudinal compression of the seedling blankets and analyze their compression characteristics. The mechanical equilibrium equation for seedling blankets on the seedling trays was established. Integrating the compression characteristics of the seedling blankets, a compression model was established to predict the amount of longitudinal compression of rapeseed blankets on the seedling tray. Theoretical analysis revealed that the main factors influencing seedling compression were: the moisture content of the blanket, the thickness of the blanket, the seedling tray tilt angle, and the friction coefficient between the seedling tray and seedling blanket.

The effect of the seedling tray tilt angle (A), the seedling blanket moisture content (B), and the seedling blanket thickness (C) on the longitudinal compression (Y_1), the coefficient of variation in the longitudinal seedling conveying distance (Y_2), and the qualified-block-cutting rate (Y_3) were investigated by test in this study. The goal of the optimization was to reduce the compression of the seedling blanket and improve the uniformity of longitudinal seedling conveying and the rate of qualified block cutting.

The optimization results showed that the predicted optimal parameters were a seedling tray tilt angle of 50.14°, a seedling blanket moisture content of 71.86%, and a seedling blanket thickness of 22.13 mm. Using these parameters, the transplanter achieved a longitudinal compression of 18.17 mm, a coefficient of variation in the longitudinal seedling conveying distance of 1.142, and a qualified-block-cutting rate of 90%. Field test verification was conducted, and the transplanter achieved a longitudinal compression of 16.67 mm, a coefficient of variation in longitudinal seedling conveying distance of 1.41, and a qualified-block-cutting rate of 92.2% using the optimal parameters.

The optimized parameter scheme resulted in a high-performance operation that satisfies actual operation requirements for conveying and picking seedlings and provides theoretical and empirical support for the optimization design of the seedling conveying mechanism of automatic transplanters and mechanized rapeseed blanket seedling cultivation. The lack of longitudinal precision in seedling conveying can be solved by appropriately optimizing and designing the longitudinal seedling conveying mechanisms. This paper presented two improved longitudinal seedling conveying methods. One approach involves cultivating seedling blankets with a convex–concave bowl-shaped bottom and designing conveyor belts that engage with the bottom of the seedling blankets to limit longitudinal compression. Another approach involves designing a clamping device for the upper part of the seedling blanket. Ensuring that the design of these mechanisms does not affect the seedling placement efficiency will be a key focus of further research.

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