Design and optimization of seedling-feeding device for automatic maize transplanter with maize straw seedling-sprouting tray

Zhang Wei[1], Niu Zhaojun[2], Li Lianhao[1*], Hou Yongrui[1]

(1. *College of Engineering, Heilongjiang Bayi Agricultural University, Daqing163319, China*; 2. *Tropical Agricultural Machinery Research Institute, Chinese Academy of Tropical Agricultural Sciences, Zhanjiang 524091, China*)

Abstract: This research aimed to solve current problems in the process of maize transplanting in China such as large labor intensity, low working efficiency and poor quality. On the basis of the structure of a seedling-sprouting tray made of maize straw and the agronomic requirements of maize production, this study developed a new feeding device for such a sprouting tray, determined the dimensions of the key components in a virtual environment via Solid Edge software and obtained optimal working parameters in combination with Matlab. Some tests on field validation and maize production were conducted as well. The test results showed the importance of the working parameters on an upright degree in descending order (as well as the best working parameters) to be the vertical angle of seedling planting (13.14°), the forward speed of locomotion (0.57 m/s), and the horizontal angle of the seedling box (22.5°). The standard deviation of the field validation was 6.04%, which was within the allowable range to meet the requirements of maize transplanting. Compared with maize transplanting machines (and manual transplanting operations) on the current market, the labor inputs, as well as the rates of spacing and upright degree qualification, omitted planting and the yield using the new feeding device for automatic transplanter with maize straw seedling-sprouting trays increased 0 (6.9%), 0 (3.1%), 0 (4.5%) and 0 (−1.0%), respectively; whereas, the manufacturing cost was reduced by 35.5%. The results can provide a technical basis and reference for subsequent development of automatic transplanters with maize straw seedling-sprouting trays.

Keywords: maize, seedling-sprouting tray, automatic maize transplanter, seedling-feeding device, optimization

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1 Introduction

Maize was the first major crop cultivated in Heilongjiang Province, China. In 2014, its total planting area and the total yield were 6.37×107 hm^2 and 28.139 million tons, respectively, accounting for 46.1% of the total planting area and 51.7% of the total crop yield. The maize production of this province, the largest commodity grain production base, has played a very important food-security role in China[1].

Currently in Heilongjiang Province, maize is most commonly directly sowed in the spring[2], which is more convenient and labor-efficient. But the low ground temperature in this season is a major bottleneck restricting the growth of maize crops[3].

A large number of field tests have proved that the transplanting technology of seedling-sprouting trays made of maize straw is one of the most effective means to break through the aforementioned maize-production bottleneck[4].

At the beginning of the 21st century, certain areas of Heilongjiang Province, such as Nahe City, Hailun City,

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Biographies: Zhang Wei, PhD, Professor, Majoring in agricultural machine. Email: zhang66wei@163.com. **Niu Zhaojun**, Master, Majoring in agricultural machine. Email: niuzhaojun0818@163.com. **Hou Yongrui**, Master, Majoring in agricultural machine. Email: 307068001@qq.com.

***Corresponding author: Li Lianhao**, PhD, Lecturer, Postdoctoral Fellow at Henan Agricultural University. Majoring in intelligent agricultural machinery, water-saving theory and technology. Mailing address: College of Mechanical and Electronic Engineering, Henan Agricultural University, No.63, Nongye Road, Jinshui District, Zhengzhou, 450002, China. Email: lianhao8002@126.com.

Qinggang County, Anda City and Mingshui County, tried manual transplanting of maize[5]. The yield obviously increased, but problems still existed, including large labor-intensive input, low working efficiency, and a low degree of working standardization. Concurrently, with annual increases in rural labor transfers, and continually increasing labor costs[6], transplanting such large areas of maize crops cannot be achieved by manual means alone. Therefore, the mechanization of maize seedling transplanting is imperative.

At the beginning of the 20th century, international researchers and institutions started trying to mechanize maize seedling transplantation. In the 1920s, researchers in certain developed countries such as France, Holland and Italy devised the UT-2, MT and AUTOMA clamp types of maize transplanters, respectively[7]. In the former Soviet Union, the CKH-6A and CKB-4A disk-cramping types were developed[8]. In China, a developing country, Wu Wei and his group developed the 2YZ, 2ZT, and 2Z-2 clamp types and the 2ZY-2, 2ZB-2, and 2ZQ chain-cramping types[9]; Yu Xiugang and his group developed the 2YZ-4, 2ZB-6, and 2ZYB-2 hanging-cup types[10]; whereas, Feng Jun and his group designed the 2ZB-4, 2ZDF, 2ZY-200 and 2ZG-2 seedling conduction tube types[11]. The transplanting and yield-improving effects of the aforementioned maize transplanters were remarkable, but most of them were semi-automated methods that also required manual operations[12]. The existing problems, such as the low speed of manual transplanting, large labor intensity and low working efficiency, cannot meet the actual needs in a large transplanting area.

In view of the aforementioned problems, researchers at Heilongjiang Bayi Agricultural University used maize straw as the main material to devise a seedling-sprouting tray for the first time by using certain physical methods which can break through the restrictive bottleneck in maize cultivation.

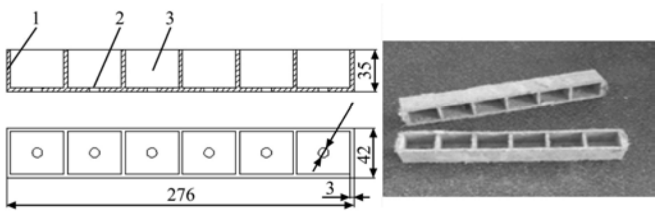
Taking a sprouting tray made of maize straw as the seedling carrier, we developed a seedling-feeding device for an automatic transplanter mounted on this type of sprouting tray as an effective solution to a series of problems in the traditional mechanical operations of maize transplantation in China.

Field tests have verified that this device, which has strong regional adaptability, a good working effect, and a high degree of automation, can serve as a good mechanical carrier for mechanical maize transplantation.

2 Structural and functional parameters of maize straw seedling-sprouting tray

2.1 Structure

In accordance with the general concept of a seedling-sprouting tray in combination with the specific agronomic requirements of maize production, the maize straw sprouting tray used in this research (shown in Figure 1) consisted of pot holes, vertical edges, a vent and vertical seedling-feeding holes[13].



1. Vertical edges 2. Vent and vertical seedling-feeding holes 3. Pot hole

Figure 1 Maize straw seedling-feeding tray

The pot holes were the growing spaces for the maize seeds. The vertical edges were the coupling portion of an adjacent maize straw seedling-sprouting tray (the vertical edges being shared by adjacent pot holes) and were mainly used to maintain the integrity of the tray. The vent and vertical seedling-feeding holes were used to ensure e bottom of the tray and realize orderly vertical transplanting.

Combined with the agronomic requirements of maize production[14-16], the main structural parameters of the sprouting tray are listed in Table 1.

Table 1 Main structural parameters

Items	Values
Total number of pot holes	6
Seeding quantity of single pot hole	1
Horizontal dimension/mm	276
Vertical dimension/mm	42
Depth of pot hole mm	32
Thickness/mm	35

2.2 Functional requirements

In order to meet the requirements of the follow-up operations in combination with the actual maize production in Heilongjiang Province, the transplanting and seedling-feeding work maize needed to meet the following requirements[17,18]:

1) Emergence rate of maize before transplanting greater than 98%;

2) Row spacing at 60-70 cm with adjustable plant spacing;

3) Upright degree of maize seedlings after transplanting not less than 85%;

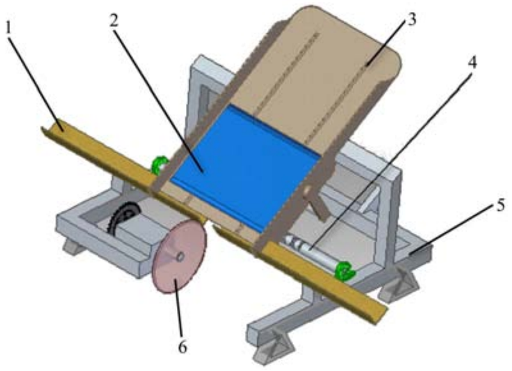
4) Seedlings injury rate less than 1.2%;

5) Omitted planting rate less than 2.7%.

3 Design and function of seedling-feeding device

3.1 Overall design

In consideration of the transplanting requirements and structure of a maize straw sprouting tray, a seedling-feeding device was developed. Its structure is illustrated in Figure 2, and the main technical parameters listed in Table 2.



1. Rack 2. Vertical feeding mechanism 3. Seedling box 4. Spiral shaft 5. rack 6. Planting mechanism

Note: AB- axial length of spiral groove, CD- inner distance of seedling box.

Figure 2 Schematic diagram of seedling-feeding device

Table 2 Main technical parameters

Items	Values
Dimensions (work)/mm	2312×1562×412
Number of operations	2
Row spacing of transplanting/mm	65
Spacing of transplanting/mm	15-30
Seedling planting speed/min	≥90
Operational efficiency/km^2·h^{-1}	0.15-0.6
Supporting power/kW	42-70

The feeding device for the sprouting tray was mainly composed of the rack, seeding boxes, feeding mechanisms and power transmission system. A seeding box was used for storing the sprouting tray. The feeding device consisted of horizontal and vertical mechanisms which finished the horizontal and vertical feeding operations of the sprouting tray in tandem with the cutting operations of seedling needles[19,20]. The power transmission system was composed of a power shaft, a spiral shaft and a shifting fork, mainly used for transmitting the input power of the tractor to the various working parts[21,22].

3.2 Operational process

In the process of maize transplantation, after a growth period of about 38 d, we first placed the maize straw seedling-sprouting tray (pictured in Figure 3) into the seedling box, the furrow opener and the irrigation system, respectively, by digging holes for irrigation (0.5 L/hole) in the soil in a forward direction[23-25]. Under the moving parts of the seedling-feeding device and seedling needles, the sprouting tray was cut into blocks and orderly transferred to the soil apertures.

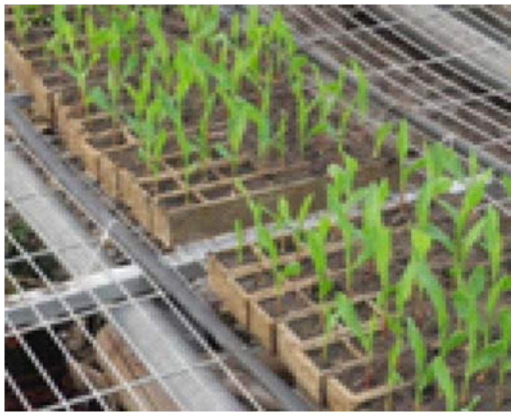
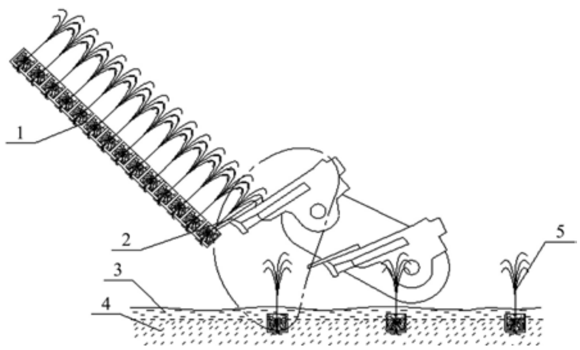


Figure 3 Seedlings before transplanting

The blocks of soil were covered with a lid to complete the transplantation process. The straw sprouting tray, having completed a life cycle, was also degraded in the soil. The entire process is illustrated in Figure 4.



1. Maize straw seedling-sprouting tray 2. Planting mechanism 3. Water layer 4. Soil 5. Sprouting tray in block after transplantation

Figure 4 Transplantation process utilizing maize straw seedling-sprouting tray maize straw

3.3 Motion simulation of seedling-feeding device

To facilitate the design and shorten the design cycle, a motion simulation of a virtual sample device was constructed in a virtual environment with Solid Edge software. The results of the analysis were as follows:

1) The axial distance L_{AB} (depicted in Figure 5) played a decisive role in the size of the seedling door, as expressed in Equation (1):

$$L_1=L_{CD}-L_{AB} \tag{1}$$

where, L_1 is the width of the seedling door, mm; L_{AB}, the axial length of the spiral groove, mm; L_{CD}, the inner distance within the seedling box, mm.

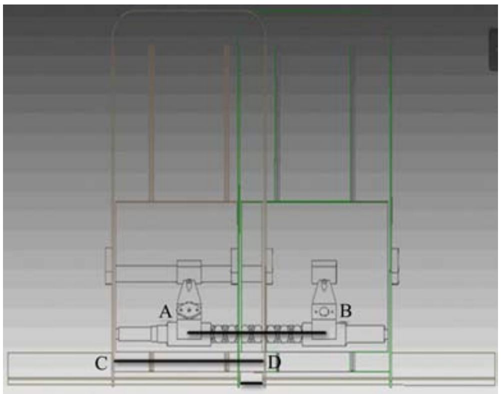


Figure 5 Motion simulation of working process

2) The dimensional precision when the spiral shaft was processing needed to be verified to avoid the phenomenon of "getting stuck" in the transplanting operation[26].

4 Design of key components

4.1 Horizontal seedling-feeding device

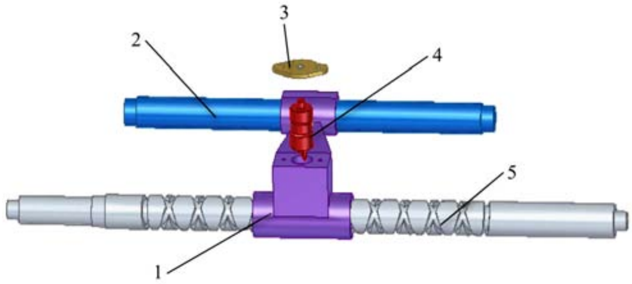
4.1.1 Feeder requirements

1) In accordance with the size of the maize straw seedling-sprouting tray, the horizontal spacing should be 45.5 mm when transplanting. The maximum allowable displacement amount is 4 mm when cutting the seedlings.

2) The next transplanting operation should be run after finishing six horizontal operations.

4.1.2 Structure

The horizontal feeding device is one of the key components of the automatic transplanter, the bearing of which is a spiral shaft, of which the diameter, the pitch and the helix angle are the key parameters. The modeling of the shaft mechanism is illustrated in Figure 6.



1. Sliding sleeve 2. Seedling box connecting rod 3. Slide plate 4. Slider 5. Spiral shaft

Figure 6 Modeling of spiral shaft mechanism

1) Shaft diameter

The shaft of the feeding device is mainly exposed to shear stress during the working process, as expressed in Equation (2):

$$\tau_T=\frac{T}{W_T}=\frac{9.55\times10^6 P}{0.2d^3 n}\leq[\tau_T] \tag{2}$$

Derivation:

$$d\geq\sqrt[3]{\frac{9.55\times10^6 P}{0.2n[\tau_T]}}=\sqrt[3]{\frac{9.55\times10^6}{0.2[\tau_T]}}\cdot\sqrt[3]{\frac{P}{n}}=C\sqrt[3]{\frac{P}{n}}$$

where, τ_T is the shearing force, MPa; $[\tau_T]$ is the allowable shearing force, MPa; T is the torque, N·mm; W_T is the anti-torsional section modulus, mm^3; P is the power, kW; n is the shaft speed, r/min; d is the cross-section radius of the shaft, mm; C is the safety factor.

On the basis of the operating conditions, the spiral shaft selection was 40Cr, the diameter after inspection being $d\geq10.53$ mm.

In practical application, we set the groove to make the radius increase by 3%; therefore, $d\geq10.875$ mm and the shaft diameter, R_1=22 mm.

2) Pitch and helix angle of shaft

(1) Pitch

The horizontal plant spacing required is 45.5 mm during the cutting operation; hence, the pitch was set at D=23 mm.

(2) Helix angle

This value is calculated by Equation (3):

$$\gamma=\arctan\left(\frac{D}{\pi R}\right) \tag{3}$$

where, γ is the helix angle, (°); D is the pitch, mm; R is the diameter, mm. After calculation, γ=18.4°.

4.1.3 Slider

The seedling box on the sprouting tray needs a horizontally reciprocating movement during transplantation; therefore, we designed a slider to drive the box during this reciprocation along the shaft. Because of this reciprocating movement, the slider requires strong wear resistance. Therefore, we used a double-circular slider, the structure of which is diagrammed in Figure 7.

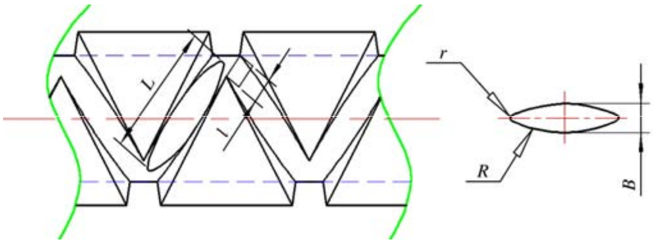


Figure 7 Schematic diagram of double circular arc slider mechanism

The double-circular structure ensures that the slider is able to move in the proper direction when it is transiting through both ends of the shaft and the cross-section of the spiral groove. The relationship is expressed in Equation (4):

$$\begin{cases} L > 2l \\ l = \dfrac{B}{\sin 2\gamma} \end{cases} \tag{4}$$

where, B is the width of the gullets, mm; γ is the spiral-lead angle, (°). L is the tangent contact surface length of the slider and spiral groove, mm; l is the width of the spiral groove, mm.

Taking B=5 mm and inserting γ=18.4° into the equation, we obtained l=8.347 mm; thus, L= 17 mm.

4.2 Vertical seedling-feeding device

4.2.1 Feeder requirements

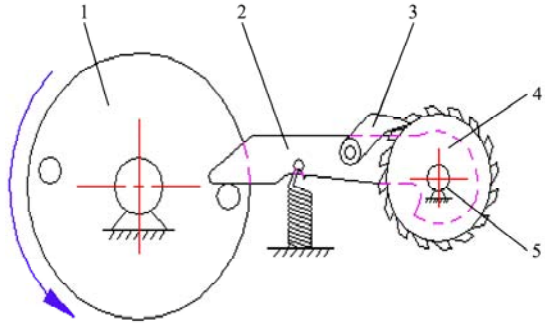
1) Intermittent feeding, spaced at 35 mm intervals.

2) The next vertical feeding should be run after finishing six horizontal operations.

4.2.2 Structural design

According to vertical seedling-feeding requirements, the feeder on a maize straw sprouting tray is mainly composed of a shifting fork, a rocker, and a ratchet, as illustrated in Figure 8.

During the transplanting, the power of the shifting fork is transmitted by the spiral shaft through the gear structure, causing the fork to continuously rotate counterclockwise when the transplanter is operating.



1. Shifting fork 2. Rocker 3. Ratchet 4. Ratchet, wheel 5. Transmission shaft

Figure 8 Structural design of longitudinal transplanter

When the seedling box is moved to each end, a plate of six sprouting trays then needs vertical replenishment. The second rocker moves into the effective working area of the two arms of the shifting fork, the spiral shaft drives the shifting fork rotation one lap, the shifting arms move the rocker twice, and the ratchet pawl pushes the ratchet clockwise, thereby rotating two ratchets. At each iteration, the spring drives the rocker, causing it to return to the initial position; and the coaxial belt completes the vertical replenishment with a 42 mm vertical displacement. At this time the slider merely moves into the return track through the buffer area at both ends of the spiral groove, thereby driving the seedling box to horizontal-feeding mode.

1) Number of ratchets

The diameter of a ratchet is calculated by equation (5):

$$\frac{1}{c} \times 2\pi R_1 = \frac{42}{2} \tag{5}$$

where, c is the number of ratchets; R_1 is the diameter of a ratchet, mm.

The vertical distance in which the seedling box can hold back is 55 mm; hence, $R_1 \leq 55$ mm. The number of ratchets should be 15; thus, R_1=50.4 mm, as amended.

2) Ratchet rotation angle

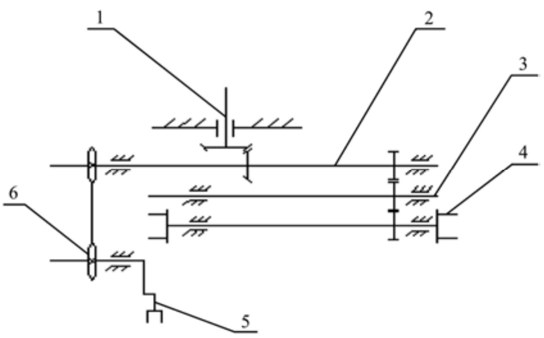
Therefore, ratchet rotation angle $\theta = \dfrac{360^\circ}{15} = 24^\circ$.

The aforementioned conditions can meet the needs when the seedling box is moved to each end and the shifting fork moves the ratchet twice to achieve vertical seedling-feeding at 42 mm displacement. Thus, the sprouting tray is replenished.

4.3 Power transmission system

The power transmission system is diagrammed in

Figure 9. The tractor supplies power to the feeding device, which is articulated by a three-point suspension structure that connects the power by a cardan joint and a power-input shaft, then transmits the power to the horizontal-feeding spiral shaft, the vertical-feeding shifting fork and the planting device via the power transmission shaft (shown in Figure 4). The rotary spiral shaft drives the hyperboloid slider in a collision movement in the spiral groove when transplanting and also drives the seedling box in a straight reciprocating movement by connecting the sleeve in the shaft direction. Concurrently, the planting mechanism at the seedling door, driven by the chain drive mechanism, works on picking and planting the seedlings in tandem with the feeder box. The seedling box then moves to each end when a row of seedlings has been picked. Then the shifting fork shifts the ratchet at the back of the seedling box and drives the coaxial feeding belt to operate on the vertical feeder. Thus, the feeding cycle circularly cooperates with the picking cycle to complete the transplanting.



1. Power input shaft 2. Power transmission shaft 3.Spiral shaft 4.Vertical feeding fork 5. Planting mechanism 6.Sprocket

Figure 9 Diagram of transmission system

To ensure that the seedling needle can effectively cut the maize sprouting tray, the power transmission ratio should meet the conditions in Equation (6):

$$\begin{cases} i_{63} = \dfrac{i_6}{i_3} = \dfrac{1}{2} \\ i_{23} = \dfrac{i_2}{i_3} = \dfrac{1}{1} \end{cases} \tag{6}$$

5 Optimization of working parameters

5.1 Test conditions

The test was conducted in the soil bin laboratory in the College of Engineering at Heilongjiang Bayi Agricultural University. This trial was to test a seedling-feeding device on a maize straw sprouting tray, powered by a TCC-3 soil-bin automated vehicle, as established and reformed by the university.

5.2 Test design

A large number of tests indicated that the horizontal angle of the seedling box (Z_1), the vertical angle of seedling planting (Z_2), and the forward speed of locomotion (Z_3) were the main factors influencing the feeding device. To optimize the working parameters, the tests used the rotational regression method for experimentation. The coding levels of the factors are listed in Table 3.

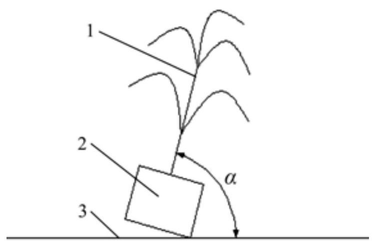
Table 3 Coding levels of factors

Coding	Z_1/(°)	Z_2/(°)	Z_3/m·s^{-1}
Highest (+1.682)	45	20	0.6
High (+1)	40	18	0.5
Neutral (0)	33.5	16.5	0.4
Low (−1)	27	15	0.3
Lowest (−1.682)	22	13	0.2
Change interval	6.75	2	0.1

5.3 Evaluation indicator

The evaluation indicator for the testing was the upright degree. In the evaluation criteria of previous research, the operational quality of a rapeseed transplanting machine specified the percentage of the number of plantings for which the angle of a seedling stem with the ground was not less than 30°, thereby accounting for the number of actual transplanted seedlings, excluding the number of omitted, buried, injured and lodging seedlings[27-30].

In accordance with the growth features of a maize straw seedling-sprouting tray, the angle of the tray with the ground was set at α. As illustrated in Figure10, $\alpha \in [80°, 90°]$ was excellent, $\alpha \in [65°, 80°]$ was good, $\alpha \in [45°, 65°]$ was qualified, and $\alpha < 45°$ was disqualified[31].



1. Maize seedling 2. Block of straw sprouting tray 3. Ground

Figure 10 Upright degree

The trials tested each sample for the angle of its stem with the ground and calculated the upright degree by the ratio of the number of qualified seedlings with the total number of samples, as calculated by equation (7):

$$Z_L = \frac{Z_H}{Z_Q} \times 100\% \tag{7}$$

where, Z_L is the upright degree, %; Z_H, the number of qualified seedlings; Z_Q is the total number of samples.

5.4 Data processing

The tests used the rotational regression program for experimentation, analyzed the results by stepwise regression using SPSS Statistics software, and established the mathematical model. Then we analyzed the interaction between a single factor and various pairs of factors to determine the contribution of their respective degrees of influence on the target, and solved the equation for the optimal value by using the optimization toolbox in Matlab software. Finally, we verified the accuracy of the theoretical analytical results through field testing.

5.5 Analysis of results

5.5.1 Function construction

A stepwise regression analysis of the experimental results was implemented via SPSS, setting the evaluation indicator upright degree (y) as a variable, setting the vertical angle of seedling droppings as well as the forward speed of locomotion and the horizontal angle of the seedling box as arguments. Then the significant coefficient was selected and the non-significant coefficient (Table 4) eliminated to establish the regression Equation (8):

$$y = 77.005 - 10.816Z_1 - 4.38Z_2 - 5.78Z_3 \tag{8}$$

Table 4 Factor analysis

Model		Non-standardized coefficients		t	Sig
		B_C	Standard deviation		
1	(Constant)	76.218	1.621	47.030	0
	Z_1	−10.277	2.103	−4.887	0
2	(Constant)	76.794	1.312	58.517	0
	Z_1	−10.277	1.690	−6.081	0
	Z_3	−5.588	1.579	−3.539	0
3	(Constant)	77.005	1.085	71.003	0
	Z_1	−10.816	1.404	−7.704	0
	Z_3	−5.783	1.304	−4.435	0
	Z_2	−4.380	1.359	−3.224	0.004

5.5.2 Dimension-reduction analysis

To analyze the effect between pairs of factors and the evaluation index, we conducted a two-factor interactive analysis of the test results by the dimension-reduction method, fixing N–2 factors in the quadratic regression model with N factors to obtain the regression model. Following is a discussion of the influence of those different factors on the upright degree.

1) Horizontal angle of seedling box and vertical angle of seedling planting

When analyzing the influence of the interaction between the horizontal angle of the seedling box Z_1 and the vertical angle of seedling planting Z_2 on the upright degree y, we set the forward speed of locomotion Z_3 at the fixed value 0; hence, the regression equation was expressed as Equation (9):

$$y = 77.005 - 10.816Z_1 - 4.38Z_2 \tag{9}$$

The influence of the interaction between the horizontal angle of the seedling box and the vertical angle of seedling planting on the upright degree is graphed in Figure 11.

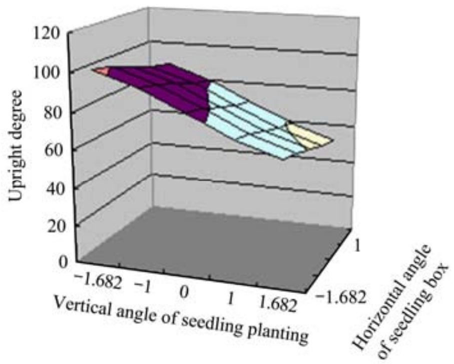


Figure 11 Effects of horizontal angle of seedling box and vertical angle of seedling planting on upright degree

The areas of relatively high upright degree appeared when both of these and–angles–were below the 0 level. When the vertical angle is fixed, the upright degree will gradually increase with the decrease in the horizontal angle. When the horizontal angle was fixed, the upright degree gradually increased with the decrease in the vertical angle. This phenomenon occurred mainly because a seedling-box angle that was too large could cause the vertical angle of planting to be too large and consequently fall over easily. Both the horizontal and the vertical angles needed to match reasonably to increase the upright degree. Therefore, the vertical angle of seedling planting was the major factor influencing the upright degree[32].

2) Horizontal angle of seedling box and forward speed of locomotion

When analyzing the influence of the interaction between the horizontal angle of the seedling box Z_1 and the forward speed of locomotion Z_3 on the upright degree y, we set the vertical angle of seedling planting at Z_2=0; hence, the regression equation was expressed as (10):

$$y = 77.005 - 10.816Z_1 - 5.73Z_3 \tag{10}$$

The influence of the interaction between the horizontal angle of the seedling box and the forward speed of locomotion on the upright degree is graphed in Figure 12. When the forward speed of locomotion was at the −0.594 level and the horizontal angle of the seedling box was below 0, the upright degree was the highest. When the forward speed was fixed, the upright degree changed little with a change in the horizontal angle. When the horizontal angle was fixed, the upright degree changed significantly with a change in the forward speed. Too large or too small a change in the forward speed caused a decrease in the upright degree. These changes occurred when the forward speed of locomotion was the same as that of the horizontal component velocity of the seedlings knife but in the opposite direction[33,34], when both were approaching planting at zero speed and the seedlings' landing was most stable. Therefore, the horizontal angle of the seedling box was the major factor influencing the upright degree.

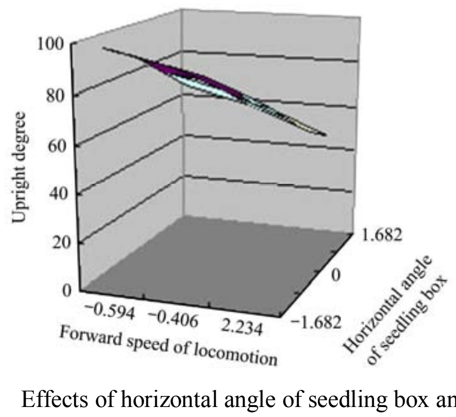


Figure 12 Effects of horizontal angle of seedling box and forward speed of locomotion on upright degree

3) Vertical angle of seedling planting and forward speed of locomotion

When analyzing the influence of the interaction between the vertical angle of seedling planting Z_2 and the forward speed of locomotion Z_3 on the upright degree, we set the horizontal angle of the seedling box at Z_1=0; thus, the regression was expressed as Equation (11):

$$y = 77.005 - 4.38Z_2 - 5.783Z_3 \tag{11}$$

The influence of the interaction between the vertical angle of seedling planting and the forward speed of locomotion on the upright degree is graphed in Figure 13. When the forward speed was at the −0.594 level and the vertical angle was below 0, the upright degree was relatively higher. When the forward speed was fixed, the upright degree changed little with the change in the vertical angle. When the forward speed was fluctuating at the critical point of planting at zero speed, the upright degree was relatively stable. The upright degree changed more significantly when the forward speed was above the level of 0.406 than it was below that level. Therefore, the forward speed of locomotion was the major factor influencing the upright degree.

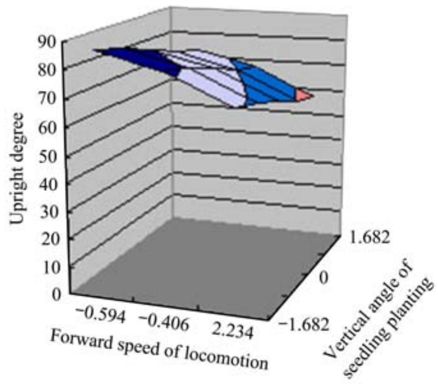


Figure 13 Effect of forward speed of locomotion and vertical angle of seedling planting on upright degree

5.6 Analysis of importance of factors

The contribution-rate method was usually used to determine the importance of the influence of various factors on the target. For the quadratic regression equation[35], we obtained the variance ratio of regression coefficients $F(j)$, $F(ij)$, $F(jj)$ and formulated the Equation (12):

$$\delta = \begin{cases} 0(F \le 1) \\ 1 - \dfrac{1}{F}(F > 1) \end{cases} \tag{12}$$

We obtained the contribution rate of each factor of the regression equation for the evaluation index y.

The formula of the contribution rate of factor j for that index-was Equation (13):

$$\Delta_j \delta_j + \frac{1}{2}\sum_{\substack{i=1 \\ i\neq j}}^{m} \delta_{ij} + \delta_{jj} \tag{13}$$

where, δ_j is the contribution of factor j as a coefficient; δ_{ij} is the contribution of interaction terms; δ_{jj} is the contribution of the quadratic term. Through comparing the value of the contribution rate[36], we can intuitively determine the importance of the influence of each factor on evaluation y.

Thus, the variance ratio of regression coefficients and the contribution rates in this test are listed in Table 5.

Table 5 Regression coefficients and contribution rates

Regression coefficient	Contribution rate
$F_{(1)}$=23.879	Δ_1=0.958
$F_{(2)}$=27.716	Δ_2=0.963
$F_{(3)}$=24.755	Δ_3=0.959

Therefore, the descending order of importance of the factors is as follows: vertical angle of seedling planting, forward speed of locomotion, and horizontal angle of the seedling box.

5.7 Optimization of working parameters

The optimization of working parameters with Matlab by solving the regression equation is as follows: horizontal angle of seedling box, 22.5° and 13.14°; forward speed of locomotion, 0.57 m/s; upright degree of sprouting tray, 89.64%.

5.8 Verification test

To adjust the testing plot for the seedling-feeding device to the optimum parameters and measure the differences in the upright degrees of several experiments and the fit of the results by theoretical analysis[37,38], the upright degree of the maize straw seedling-sprouting tray (shown in Figure 14) was determined to be 83.6%. The relative error was no more than 6.04% when compared with the optimal results, which was within the allowable range; therefore, the optimal results were reliable.

Table 6 Results of experimental verification

No.	Z_1/(°)	Z_2/(°)	Z_3/m·s^{-1}	Z_L/%	Average
1	13.14	22.5	0.57	82.32	
2	13.14	22.5	0.57	85.08	83.6%
3	13.14	22.5	0.57	83.42	

Figure 14 Verification test

6 Production test

6.1 Test conditions

The production test was conducted in Shengping Township, Anda City, Heilongjiang Province from May to October 2014. The testing ground was flat and free of both weeds and crop residues[39-41]. The ridge distance was 65 cm in black soil having a firmness of 236.7×10^4 Pa.

6.2 Test design

To verify the reliability and increase in yield from a transplanting machine equipped with a maize straw seedling-sprouting tray (T), we set two conditions. The first was to compare the seedling-feeding device on an automatic transplanter having the aforementioned type of sprouting tray (T_1), as developed by the Agricultural Machinery Engineering Science Research Institute of Heilongjiang Province, with transplantation in traditional maize production. The second was to compare manual transplanting (T_2) with traditional maize production. Therefore, we set four 1.2 hm^2 testing areas, each under the same management.

6.3 Evaluation indicator

1) Qualification rate of plant spacing

We set the distance between each two adjacent seedlings at X_i (mm) and the theoretical transplanting spacing at X_r (mm) to determine the qualification rate of plant spacing according to the relationship between X_i and X_r[42], for which the actual distance between adjacent seedlings was $X_i \in (0.5X_r, 1.5X_r]$.

Thus, the qualification rate is calculated with Equation (14):

$$Z_G = \frac{Z_{GH}}{Z_{HT}} \times 100\% \tag{14}$$

where, Z_G is the qualification rate, %; Z_{GH} is the number of spacing-qualified seedlings; Z_{HT} is the total number of seedling samples.

2) Omitted planting rate

The evaluation criteria for quality operation of a rapeseed transplanting machine specifies the measurement of distance between two adjacent seedlings. We set this measurement at X_i (mm) and the theoretical transplanting spacing at X_r (mm) to determine the number of omitted plantings according to the relationship between X_i and X_r. When the actual distance between two adjacent seedlings was $X_i \in (0.5X_r, 1.5X_r)$, the number of omitted plantings was one; when the actual distance was $X_i \in (2.5X_r, 3.5X_r)$, the number of omitted plantings was two.

Thus, the omitted planting rate is calculated with Equation (15):

$$Z_O = \frac{Z_{OH}}{Z_{OT}} \times 100\% \tag{15}$$

where, Z_O is the omitted planting rate, %; Z_{OH} is the number of omitted plantings; Z_T is the total number of samples.

6.4 Test results

The test results are listed in Table 7.

Table 7 Production test results

Indicators	T	T_1	T_2
Manual input/yuan·hm^{-2}	1233	1300	1672
Manufacturing cost/yuan	43200	67000	0
Spacing qualification rate/%	94.1	93.9	92.7
Upright-degree qualification rate/%	83.2	83.1	80.1
Omitted planting rate/%	2.2	2.3	3.2
Yield increase/%	10.2	10.0	5.7

As indicated in Table 7, T was closer to T_1 in terms of manual input, spacing qualification rate, upright-degree qualification rate, and yield increase; however, the manufacturing costs were reduced by 35.5%. When compared with T_2, the manual input was reduced by 26.26%; the spacing qualification rate increased by 1.4%; the upright-degree qualification rate increased by 3.1%; the omitted planting rate was reduced by 1.0%; and the yield increased by 4.5%. These results demonstrate that the design, theoretical analysis and parameter selection were reasonable for the seedling-feeding device on the automatic transplanter on the maize seedling-sprouting tray used in this research[43-45].

7 Conclusions

In this study, a stepwise regression analysis of multi-factor experimental results was implemented via SPSS, a mathematical model for the main parameters of a seedling-feeding device on the automatic transplanter on a maize seedling-sprouting tray formulated, and a field test was conducted. The conclusions were as follows:

1) The working parameters influencing the upright degree were ranked in descending order (and best working parameters) as follows: vertical angle of seedling planting, forward speed of locomotion, and horizontal angle of seedling box.

2) The optimization of working parameters was achieved when the horizontal angle of the seedling box was 22.5°; the vertical angle of the seedling box, 13.14°; the forward speed of locomotion, 0.57 m/s; and the upright degree of the maize straw seedling-sprouting tray, 89.64%.

3) Compared with maize transplanting machines currently on the market, the labor inputs, as well as the rates of spacing and upright degree qualification, omitted planting and the yield of our new feeding device for the automatic transplanter on a maize straw seedling-sprouting tray were essentially the same; however, the manufacturing cost was reduced by 35.5%. Compared with manual transplanting operations, the rates of spacing and upright degree qualification as well as the yield increased by 6.9%, 3.1% and 4.5%, respectively; whereas, the planting omission rate was reduced by 1.0%.

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