RESEARCH ON THE TRAY CONVEYING AND OUTPUT DEVICE OF AN AUTOMATIC TRAY PLACEMENT MACHINE FOR MULTI-ROW RIGID RICE SEEDLING TRAYS
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多行水稻硬质育秧盘全自动摆盘机送盘与出盘装置研究

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ABSTRACT
To address the issue of height disparity between the output device of the tray placement machine and the seedbed in stacked-tray germination under enclosed conditions - which can lead to vibration and displacement when trays are placed - a slide-type output device with a buffering function equal to the height difference was designed to ensure gentle placement of seedling trays. A three-factor, five-level quadratic orthogonal rotational combination test was conducted using Adams software for simulation analysis. The test factors included the horizontal inclination angle of the tilting frame, the horizontal inclination angle of the sliding plate, and the speed of the seedling tray pusher. Evaluation indices included the qualification rate of tray spacing, the qualification rate of alignment, and the efficiency of tray placement. Test results were analyzed using Design Expert 13 software, and multi-objective parameter optimization was performed. The optimal parameter combination was determined as follows: a tilting frame inclination angle of 15°, a sliding plate inclination angle of 18°, and a tray pusher speed of 0.16 m/s. Field trials conducted to validate these parameters resulted in a 96.11% qualification rate for tray spacing, a 95.89% alignment qualification rate, and a tray placement efficiency of 714 trays per hour - within 1% of the theoretical optimal value. These findings provide a theoretical foundation for the smooth and efficient operation of automatic seedling tray placement machines.

摘要
针对叠盘暗室育秧模式下摆盘机因出盘装置与苗床之间存在高度落差，导致秧盘着床时易产生震动位移的问题，设计了一种具有落差缓冲能力的滑板式出盘装置，实现秧盘的平稳摆放。通过 Adams 软件仿真分析，以倾斜架水平倾角、出盘滑板水平倾角、推盘推杆速度为试验因素，秧盘间距合格率、排齐率、摆盘效率为试验指标，进行三因素五水平二次正交旋转组合试验。应用 Design Expert 13 软件对试验结果进行分析并进行多目标参数组合优化，确定仿真最佳参数组合为：倾斜架水平倾角 15°，出盘滑板水平倾角 18°、推盘推杆速度 0.16m/s，并通过田间试验验证得到秧盘间距合格率 96.11%，排齐率 95.89%，摆盘效率 714 盘/h，与理论优化值误差小于 1%。研究结果为摆盘机平稳摆盘提供理论基础。

INTRODUCTION

Rice is one of the most important grain crops in China, with total output ranking first in the world. Heilongjiang Province is the main rice-growing region in China, with an annual rice output that continues to rank first in the country (*Yan et al., 2023; Li et al., 2024*). As Heilongjiang Province (*Xue et al., 2024*) is a high latitude cold region prone to cold damage at low temperatures when sowing in spring, relying on constant temperature stacked seedling tray darkroom rice seedling cultivation can improve the quality of rice seedlings and shorten the rice-planting cycle (*Li et al., 2021*). However, manual seedling tray placement is labor-intensive, so using a seedling tray placement machine reduces labor requirements and intensity (*Cheng et al., 2025; Li et al., 2020*).

The existing seedling tray placement devices can be divided into two types according to the seedling tray-out mode *(Pan et al., 2024; Li et al., 2018; Yang et al., 2023)*. One type uses a seedling tray placement machine with a fixed truss to move to the designated position. The storage frame servo controls the seedling tray's movement status. When the servo opens, the lowest seedling tray falls into the seedling bed under its own gravity to achieve orderly seedling tray placement. The other type uses a seedling tray placement machine with a conveyor to transport the seedling tray to the seedling tray-out device. Finally, a pushing device throws the seedling tray into the seedbed. In the latter case, the seedling tray is transported to the discharge device by a tractor via a conveyor belt, and is then thrown into the seedbed by a pushing device. Regardless of how the seedling tray is discharged, due to the height difference between the seedling tray device and the seedbed, the seedling tray will vibrate and displace when landing on the bed. This results in the seedling tray not being placed neatly and can even cause the phenomenon of 'overlap'. This not only wastes the seedbed, but also makes it easy for weeds to grow in the cracks of the seedling tray. This makes it difficult for the subsequent disking operation (*Yan et al., 2024*).

Currently, many scholars at home and abroad have conducted research on rice seedling devices. For example, the precision automated production line from Dutch company *Visser (2016)* is equipped with a special device for rice seedling cultivation that can accommodate seedling trays of various sizes and has a production efficiency of 1250 trays per hour. However, such equipment is relatively expensive to purchase, and the automated production lines developed in Europe and the United States are mainly aimed at vegetable and flower cultivation, so they have not yet been widely used in China (*Luo et al., 2019*). For example, indoor rice seedling cultivation equipment developed by companies such as *Kubota (2024)* and *Yanmar (2024)* is highly integrated, achieving a high degree of automation in factory-based seedling cultivation. Its precision tray feeding mechanism has a complex structure and an operating efficiency of over 1000 trays per hour *(Iseki et al., 2024).* The degree of automation is higher and it can realize the automatic placement of seedling trays. However, these models are expensive and have high installation and commissioning requirements, making them difficult to implement in China's agricultural production. In China, an earlier hand-pushed, trackless seedling tray placement device has a lower degree of automation and needs to be controlled manually, but because of its simple structure and ease of operation, it is widely used for small-scale household seedling tray placement operations (*Lv et al., 2018*).

Zhang Xiuhua et al., (*2018*), developed an articulated automatic placement machine for vegetable seedling hole trays, featuring a high degree of automation. However, the robotic program costs were too high for large-scale rice seedling tray placement. *Xie Lianshuang et al.,* (*2015*), developed a machine for potting rice seedlings, which uses a motorized rod propulsion device on a conveyor belt to place seedling trays in greenhouses. *Xia Xudong et al.,* (*2021*), designed a double cam-controlled seedling tray placement trolley, which moves along a truss to the designated area and automatically arranges the trays by separating them using a dual-cam mechanism.

This paper aims to address the above challenges by investigating an automatic seedling tray placement machine for multi-row rigid rice seedling trays. To ensure smooth tray placement without vibration or spacing gaps, the machine is equipped with a slide-type tray output mechanism featuring a fall-buffering design. One end of the slide naturally aligns with the seedbed under its own weight, enabling stable and gap-free placement of seedling trays.

MATERIALS AND METHODS

Overall structure and working principle

The automatic seedling tray placement machine for multi-row rigid rice seedling trays primarily consists of a conveyor belt, a transverse conveying device, a frame, a tray discharge mechanism, a mobility system, a height adjustment unit, a battery, and a PLC control system, as shown in Fig. 1. The frame serves as the core structural support of the entire machine and mainly includes a tilting frame, tray positioning guides, and other components. The transverse conveying device comprises a transverse pushing mechanism, a longitudinal pushing mechanism, an overturning frame, a linear push rod mechanism, and other parts. The machine is operated via a PLC control system, which coordinates the working sequence of each mechanism to achieve efficient tray conveying and placement. It moves along a fixed track to ensure stable transportation of trays, while the frame height is adjustable to accommodate different operational environments. The performance indicators of the automatic seedling tray placement machine for multi-row rigid rice seedling trays are presented in Table 1.

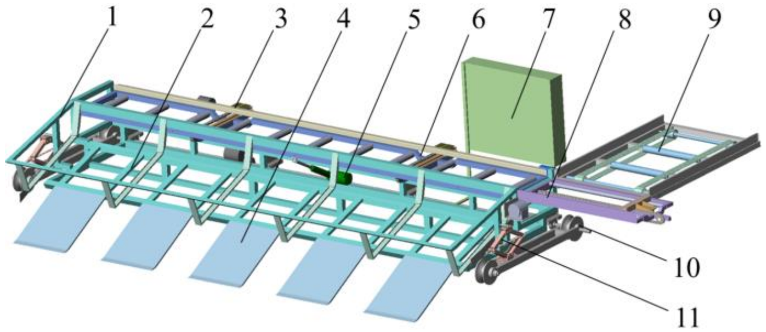


Fig. 1 – Automatic seedling tray placement machine for multi-row rigid rice seedling trays

1. Frame; 2. Tilting frame; 3. Longitudinal pushing mechanism; 4. Output device; 5. Linear pusher mechanism; 6. Flip frame; 7. PLC control box; 8. Transverse pushing mechanism; 9. Conveyor belt; 10. Mobility device; 11. Height adjustment device.

Table 1

Main technical parameters

Parameter	Number
Machine size / (length x width x height) / (mm×mm×mm)	4000×2100×950
Supporting power / W	1200
The working width is wide / mm	3000
Overall machine quality / kg	350
Number of cycles in operation / unit	5
Seedling tray size / (length x width x height) / (mm×mm×mm)	600×300×30

The working process of the automatic seedling tray placement machine for multi-row rigid rice seedling trays is illustrated in Fig. 2. First, the conveyor belt delivers seedling trays to the placement machine. The transverse pushing mechanism then transfers the trays to the flip frame. When five seedling trays are in position, the conveyor belt halts, and the linear pusher mechanism contracts, causing the flip frame to rotate to a specific angle and dock with the tilting frame. Next, the linear pusher mechanism stops, and the longitudinal pushing mechanism gently pushes the five trays down onto the seedbed. Simultaneously, the entire tray placement machine moves forward along the working direction, completing one placement cycle. Afterward, each mechanism returns to its initial position, and the process is ready to repeat.

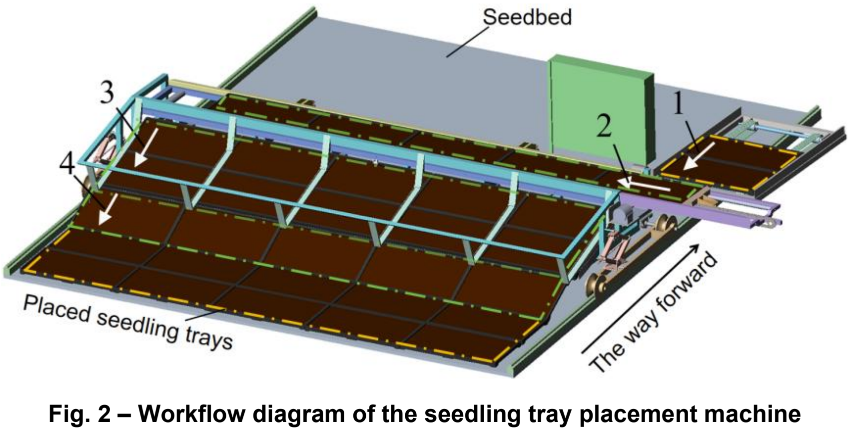


Fig. 2 – Workflow diagram of the seedling tray placement machine

1. Tray supply process; 2. Transverse conveying process; 3. Longitudinal conveying process; 4. Tray placement process.

Transverse conveying device

The transverse conveying device is an important component that affects the working efficiency of the tray placement machine and ensures the smooth transfer of seedling trays. It is primarily composed of a transverse pusher, transmission chain, push-type seedling tray pusher, flip frame, conveyor rollers, longitudinal push motor, linear pusher, and other auxiliary components. The structural diagram of the transverse conveying device is shown in Fig. 3.

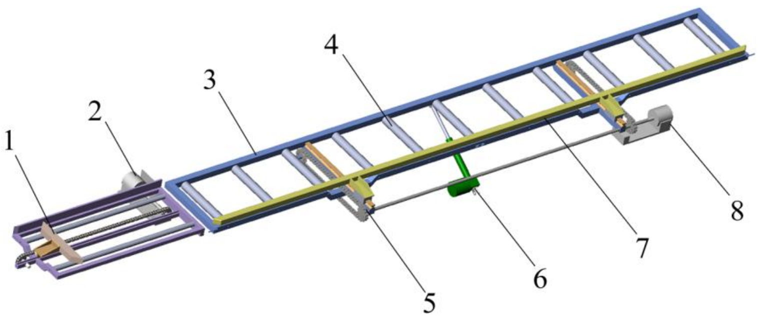


Fig. 3 – Transverse conveying device
1. Transverse pusher; 2. Transverse pusher motor; 3. Flip frame; 4. Conveyor roller; 5. Transmission chain; 6. Linear pusher motor; 7. Seedling tray pusher; 8. Longitudinal pusher motor.

The transverse pusher motor drives the transverse pusher in a continuous reciprocating motion. Once five seedling trays are pushed onto the flip frame, the linear pusher motor begins to contract, causing the flip frame to rotate around its axis to a predetermined angle. The linear pusher mechanism stops contracting once the flip frame is fully docked with the tilting frame. Subsequently, the seedling tray pusher pushes out a row of five trays simultaneously. The operating speeds of both the transverse pusher and the seedling tray pusher can be adjusted by regulating their respective motor speeds to accommodate different working requirements.

Tilting frame structure design

The horizontal inclination angle of the tilting frame directly influences the smooth movement of rice seedling trays during the discharge process. If the inclination angle is too small, the trays experience greater frictional resistance, which can lead to discharge blockages. Conversely, if the inclination angle is too large, the trays may slide uncontrollably due to gravity acting along the surface of the tilting frame, negatively affecting the placement accuracy. To analyze the forces acting on the rice seedling tray during its movement along the tilting frame, a right-angle coordinate system is established: the direction along the tilting frame is defined as the positive x-axis, and the direction perpendicular and upward from the tilting frame is defined as the positive y-axis. The force analysis of the seedling tray under these conditions is illustrated in Fig. 4.

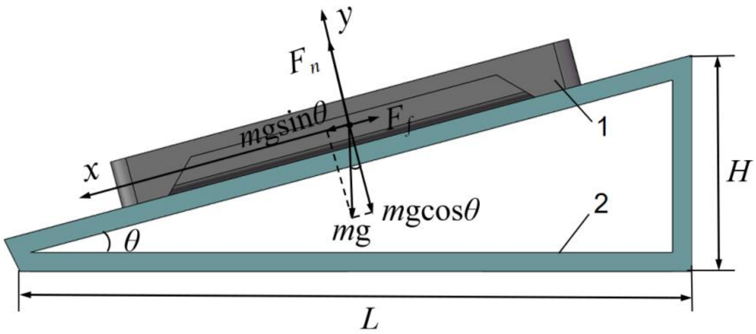


Fig. 4 – Force analysis diagram of the seedling tray
1. Rice seedling tray; 2. Tilting frame.

As can be seen from the Fig. 4, the conditions for the seedling tray to remain smooth on the tilting frame without producing the relative sliding phenomenon are as follows:

$$F_f - mg\sin\theta \geq 0 \tag{1}$$

The following equation is derived from the friction formula:

$$F_f = \mu_1 F_n = \mu_1 mg\cos\theta \tag{2}$$

where: μ_1 is friction coefficient between the seedling tray and the inclined frame; m is quality of seedling tray, (kg); F_n is the support force of the inclined frame on the seedling tray, (N); F_f is the friction between the seedling tray and the inclined frame, (N); θ is horizontal inclination of the tilting frame, (°).

Substituting formula (1) into formula (2) results in:

$$\theta \le \arctan \mu_1 \tag{3}$$

The coefficient of friction between the seedling tray and the tilting frame was determined to be approximately 0.4 based on the material properties (*Yi et al., 2023*). The maximum horizontal inclination angle θ of the tilting frame was calculated to be 21.8° using the following formula:

$$\tan \theta = \frac{H}{L} \tag{4}$$

where:

H - height of the tilting frame, (m); L - horizontal distance between the inclined supports, (m).

Due to the low height of the edge of the rice-planting shed, the overall height of the machine must be reduced. To accommodate this constraint and to make the structure of the tray placement machine more compact, the horizontal inclination angle of the tilting frame is set between 10° and 20°, and the height H is set to 0.2 m. Once the inclination angle is determined, the horizontal distance L can be calculated using formula (4).

Design of the output device

(1) Overall structure

One of the key performance indicators of the seedling tray placement machine is whether the trays are arranged neatly on the seedbed. To address the issue of vibration and displacement of seedling trays caused by the height difference between the output device and the seedbed - which often results in misaligned trays - a slide-type output device with buffering capability was developed. The device is composed of five sliding plates, each connected to the tilting frame via bolts. Under the action of gravity, the sliding plates naturally conform to the surface of the seedbed, ensuring stable and accurate tray placement without vibration or gaps. The structural diagram of the seedling tray output device is shown in Fig. 5.

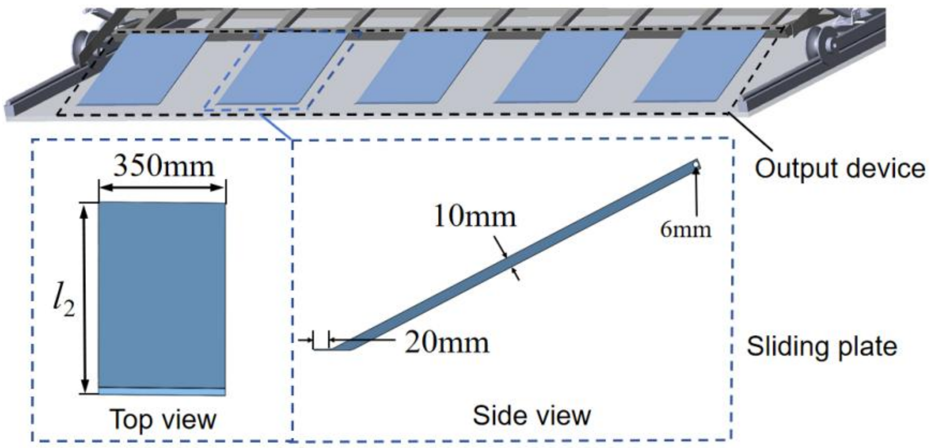


Fig. 5 – Structure of the seedling tray output device

(2) Mechanical analysis of the seedling tray placement process

During the placement of seedling trays, the angular difference between the tilting frame and the discharge sliding plate is considered in the theoretical analysis to prevent tray jamming. A right-angle coordinate system is established, where the downward direction along the tilting frame is defined as the positive x-axis, and the upward direction perpendicular to the tilting frame is defined as the positive y-axis, as illustrated in Fig. 6.

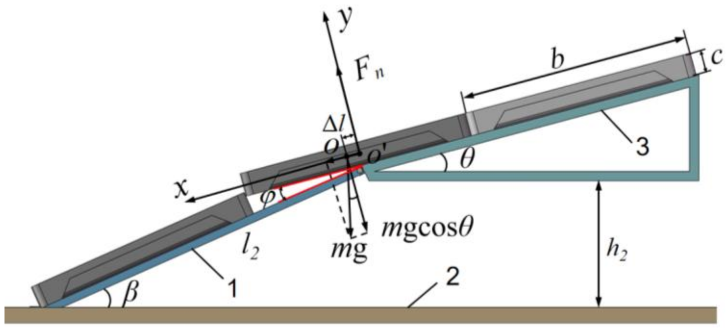


Fig. 6 – Mechanical analysis of the seedling tray placement process
1. Sliding plate; 2. Seedbed; 3. Titling frame.

As illustrated in Fig. 6, the angular difference between the tilting frame and the sliding plate is clearly shown, along with its relationship to the horizontal inclination angle of the sliding plate and the inclination angle of the tilting frame. This angular difference is expressed as:

$$\varphi = \beta - \theta \tag{5}$$

When the angular difference is large, the rear edge of the seedling tray may ride up over the front edge of the tray in front of it, causing a "hitching" phenomenon. This interference negatively impacts the proper arrangement of trays and can hinder subsequent seedling growth. In the theoretical analysis, counterclockwise rotation of the seedling tray around its center of mass is defined as positive, while clockwise rotation is defined as negative.

Define the center of mass of the seedling tray as point O, and the point of applied force as O\`. Let e represent the distance between the center of mass O and the force point O\`. Before reaching the critical state, the force point O\` coincides with the center of mass O, thus e=0. The moment equation under this condition is given by:

$$M = -mg\cos\theta \times \Delta l = 0 \tag{6}$$

After reaching the critical state, e>o. At this time:

$$M = -mg\cos\theta \times \Delta l + F_n \times 0 < 0 \tag{7}$$

where: M is torque on the seedling tray, (N·m).

In this state, the seedling tray will begin to rotate counterclockwise under the action of gravity. Simultaneously, the angle difference between the sliding plate and the tilting frame will gradually decrease. When e = 0, φ reaches its maximum value. To prevent the occurrence of the interference phenomenon at the tray outlet stage, the angle difference between the sliding plate and the tilting frame must satisfy the following condition:

$$\varphi \leq \arcsin\frac{2c}{b} \tag{8}$$

where: b is the width of the seedling tray, (mm); c is height of the seedling tray, (mm).

Based on the dimensions of the seedling tray, the width b is 300 mm, and the height c is 30 mm. When these values are substituted into formulas (7) and (8), the horizontal inclination angle β of the seedling tray sliding plate is calculated to be less than 21.53°.

Furthermore, as illustrated in Fig. 8, a direct correlation is evident between the height of the tilting frame above the ground and the length of the sliding plate.

$$h_2 = l_2 \sin\beta \tag{9}$$

where: h_2 is the height of the tilting frame above the ground, (mm); l_2 is the length of sliding plate, (mm).

To avoid interference between the seedling tray machine and the seedbed, the tilting frame is set 100 mm above the ground. Once the sliding plate's horizontal inclination has been determined, its length can be calculated using formula (9).

(3) Speed analysis of seedling tray placement process

The placement of seedling trays is influenced not only by the angle at which they land on the seedbed, but also by their relative speed at the moment of landing. To ensure smooth discharge and neat placement of the trays, it is necessary to analyze the discharge speed of the seedling tray. This speed primarily depends on two factors: the traveling speed of the tray placement machine and the pushing speed of the seedling tray pusher.

To investigate this relationship, a right-angle coordinate system is established, as shown in Fig.7, where the positive x-axis corresponds to the forward motion of the machine (locomotive direction), and the positive y-axis is defined as the direction perpendicular and upward relative to the seedbed. A theoretical analysis of the placement process is then performed based on this coordinate system.

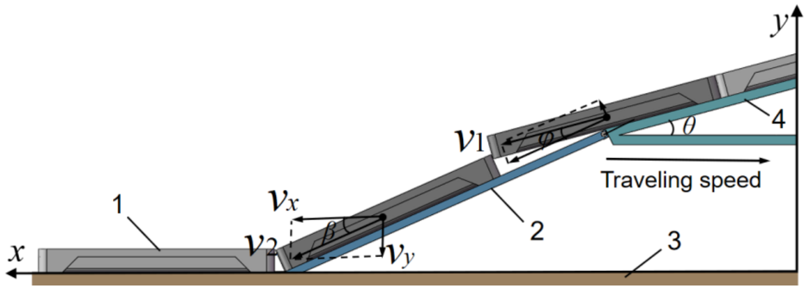


Fig. 7 – Speed analysis of seedling tray placement process
1. Placed seedling trays; 2. Sliding plate; 3. Seedbed; 4. Titling frame.

In this study, the focus is on the relationship between the pusher speed (which corresponds to the motion of the seedling trays along the tilting frame), the tray movement speed, and the relative speed of the trays along the X-axis on the sliding plate. The relationship among these three velocities is given by the following system:

$$\begin{cases} v_1 \cos\varphi = v_2 \\ v_2 \cos\beta = v_x \end{cases} \tag{10}$$

By combining these two equations, it results:

$$v_x = v_1 \cos\varphi \cos\beta \tag{11}$$

The speed of the seedling tray relative to the ground is then given by:

$$v_3 = v_0 + v_x \tag{12}$$

where:

v_0 - machine travel speed, (m/s); v_1 - speed of the pusher, (m/s); v_2 - speed of the seedling tray along the tilting frame, (m/s); v_x - relative velocity of the seedling tray along the x-axis, (m/s); v_3 - velocity of the seedling tray relative to the ground, (m/s).

When the velocity of the rice seedling tray relative to the ground $v_3 > 0$, the pusher speed exceeds the traveling speed of the tray placement machine. In this case, the seedling tray will land with excess forward motion and may overlap or press against the previously placed tray, causing tray displacement and compromising the placement quality. Conversely, when $v_3 < 0$, the pusher speed is less than the machine's travel speed. As a result, the seedling tray lands more slowly, leading to an increased gap between trays, which also affects the overall placement uniformity. Therefore, the most stable and precise placement occurs when $v_3 = 0$, meaning the seedling tray's velocity relative to the ground is zero at the moment of landing. Under this condition, the relationship between the travel speed of the tray placement machine and the pusher speed satisfies the following equation:

$$v_0 = -v_1 \cos\varphi \cos\beta \tag{13}$$

Simulation test

To evaluate the performance of the seedling tray placement machine and determine the optimal parameter values for each influencing factor, the tray discharge process was simulated and analyzed using ADAMS kinematic simulation software.

(1) Simulation parameter determination

During the simulation, the seedling tray comes into contact with other trays, the tray placement mechanism, and the seedbed. Therefore, the contact and material parameters - including those related to seedbed soil and tray materials - were determined with reference to relevant literature (*Che et al., 2023; Yi et al., 2024; Ma et al., 2025*), as summarized in Table 2.

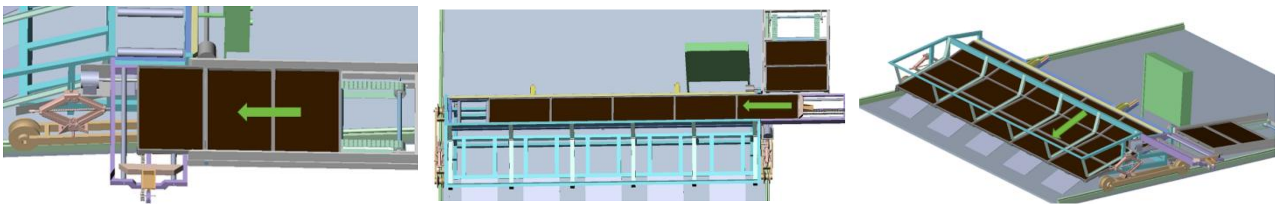
Table 2

Soil parameters of the seedling bed and the contact parameters of each material

Type of interacting material	Parameter	Numerical value
Seedling tray - Seedling tray	Coefficient of restitution	0.3
	Static friction coefficient	0.114
	Kinetic friction coefficient	0.1
Seedling tray - Tray placement machine	Coefficient of restitution	0.5
	Static friction coefficient	0.4
	Kinetic friction coefficient	0.03
Seedling tray - Seedbed	Coefficient of restitution	0.4
	Static friction coefficient	0.8
	Kinetic friction coefficient	0.2
Tray placement machine - Seedbed	Coefficient of restitution	0.6
	Static friction coefficient	0.6
	Kinetic friction coefficient	0.05
Nursery soil	Density（kg/m^3）	1189
	Poisson ratio	0.4
	Shear modulus (Pa)	1e+08

(2) Simulation modelling

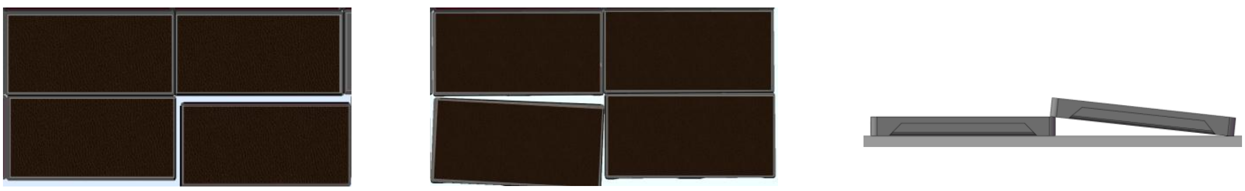
To facilitate simulation and computation, the 3D model of the seedling tray placement machine was simplified using SolidWorks and imported into ADAMS simulation software. The material properties of each component and the contact parameters between interacting parts were defined prior to assigning the driving conditions for the simulation. Although the soil inside the seedling trays is relatively viscous, it does not significantly impact the simulation results. Therefore, only the weight of the seedling tray was considered in the model. The simulation process is illustrated in Fig. 8.



(a) Seedling tray supply process (b) Transverse conveying process (c) Seedling tray placement process

Fig. 8 – Simulation process of seedling tray placement machine

To improve the accuracy and convenience of identifying unqualified seedling tray placements, visual observations can be made during the simulation to detect trays exhibiting clear signs of 'slip' (Fig. 9(a)), 'deflection' (Fig. 9(b)), or 'overlap' (Fig. 9(c)). These phenomena indicate improper placement. Following this, the post-processing module is used to plot the velocity-displacement curves of the center of mass of the seedling trays at different time points. By analyzing these curves, the placement quality of each tray can be evaluated to determine whether it meets the qualification criteria.



（a）The "slip" phenomenon （b）The "deflection" phenomenon （c）The "overlap" phenomenon

Fig. 9 – Unqualified rice seedling tray placement

(3) Evaluation indicators

According to the standardized rice planting operation regulations of Heilongjiang Province, the agronomic requirements for rice seedling tray placement are as follows: seedling trays must be placed horizontally and vertically aligned, starting from the end of the preparatory area. The first row of seedling trays serves as the reference benchmark. For subsequent trays, the horizontal misalignment with respect to the corresponding tray in the first row must not exceed 10 mm (±0.5 mm). The spacing between two adjacent seedling trays must be ≤ 5 mm (±0.5 mm). In addition, there must be no visible overlap between trays. The agronomic placement requirements for rice seedling trays are illustrated in Fig. 10.

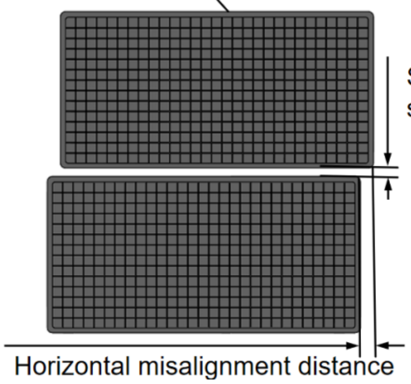


Fig. 10 – Rice seedling tray placement requirements

The qualification rate of seedling tray spacing refers to the percentage of seedling trays for which the spacing between two adjacent seedling trays is ≤5 mm (±0.5mm) and for which the 'overlap seedling trays' phenomenon (i.e. where the spacing between seedling trays is≥0) does not occur.

$$Y_1 = \frac{N_1}{N} \times 100\% \tag{14}$$

where:

Y_1 is the qualification rate of seedling tray spacing, (%); N is the total number of seedling trays placed, (unit); N_1 is number of eligible seedling trays in stock, (unit).

The qualification rate of alignment is defined as the percentage of seedling trays with a lateral misalignment distance of ≤10 mm (±0.5mm) from the corresponding seedling trays in the first row. This is calculated by using the first row of seedling trays as the reference and then determining the percentage of seedling trays with this misalignment.

$$Y_2 = \frac{N_2}{N} \times 100\% \tag{15}$$

where: Y_2 is the qualification rate of alignment, (%); N_2 is the number of seedling trays with qualifying lateral misalignment distance, (unit).

The efficiency of seedling tray placement is calculated by timing and counting the time taken to place 60 seedling trays. This time is then converted and rounded up using the following formula:

$$Y_3 = \frac{60}{t} \times 3600 \tag{16}$$

where: Y_3 is seedling tray efficiency, (trays/h); t is the time taken to successfully place 60 seedling trays, (s).

(4) Experimental method design

In order to further investigate the influence of each working parameter on the effect of seedling tray placement, the following three-factor, five-level quadratic regression orthogonal rotational combination test was carried out. According to the theoretical analysis in the early stage, the tilting frame horizontal inclination angle was set at 10~18°, the horizontal inclination angle of sliding plate at 14~22°, and the pushing speed of the seedling tray pusher at 0.10~0.22m/s. As a result, regression equations and optimization models between the test factors and the evaluation indexes were established. The coded values of the experimental factors are presented in Table 3, where X1, X2 and X3 represent the coded forms of each factor.

Table 3

Test factors coding

Coding	Factor		
	Horizontal inclination angle of tilting frame. X_1 (°)	Horizontal inclination angle of sliding trayX_2 / (°)	Pushing speed of the seedling tray pusher X_3 / (m/s)
1.682	18	22	0.22
1	16.38(16)	20.38(20)	0.1957(0.20)
0	14	18	0.16
-1	11.62(12)	15.622(16)	0.1243(0.12)
-1.682	10	14	0.10

Field validation test

To verify the optimal working parameters of the seedling tray placement machine, a field experiment was conducted at the '895 Farms' Rice Ecological Planting Base in Heilongjiang Province. The primary instruments used in the test included electronic scales, a 5-meter tape measure, and vernier calipers. The experimental trays were rigid rice seedling trays. Before the test, the pusher speed was calibrated by adjusting the motor speed, while the horizontal inclination angles of both the tilting frame and the sliding plate were adjusted to their target values using the height adjustment device. All three parameters - the horizontal inclination of the tilting frame, the horizontal inclination of the sliding plate, and the pusher speed - were set to their optimized values. To minimize experimental error, the five-point sampling method was adopted. Five positions were selected for group testing, with three repeated trials conducted at each position. The average of each group was calculated to validate the results. The experimental site is shown in Fig. 11.

Fig. 11 – Field test of the seedling tray placement machine

RESULTS AND ANALYSIS

Analysis of simulation test results

A number of simulation experiments were carried out, and the experimental results are shown in Table 4.

Table 4

Test results

Number	Factor			Performance indicators		
	X_1	X_2	X_3	Qualification rate of seedling tray spacing Y_1/(%)	Qualification rate of alignment Y_2/(%)	Efficiency of seedling tray placement Y_3/(trays/h)
1	1	1	1	88.33	90	760
2	1	1	-1	91.67	91.11	646
3	1	-1	1	93.33	90	732
4	1	-1	-1	93.33	92.78	620
5	-1	1	1	86.67	86.67	742
6	-1	1	-1	92.78	90	604
7	-1	-1	1	90	88.33	724
8	-1	-1	-1	94.44	92.22	596
9	1.682	0	0	88.89	87.78	632
10	-1.682	0	0	91.11	90	706

Number	Factor			Performance indicators		
	X_1	X_2	X_3	Qualification rate of seedling tray spacing Y_1/(%)	Qualification rate of alignment Y_2/(%)	Efficiency of seedling tray placement Y_3/(trays/h)
11	0	1.682	0	95.56	93.33	659
12	0	-1.682	0	91.67	90.56	710
13	0	0	1.682	95	93.89	782
14	0	0	-1.682	90	89.44	586
15	0	0	0	96.11	96.67	720
16	0	0	0	96.11	96.11	710
17	0	0	0	96.67	96.67	714
18	0	0	0	96.11	96.11	724
19	0	0	0	96.67	96.11	714
20	0	0	0	95	95.56	724
21	0	0	0	96.67	96.11	706
22	0	0	0	96.11	96.67	720
23	0	0	0	96.11	96.11	724

ANOVA was used to analyze the data in Table 4 and obtain the regression models for the rice seedling tray spacing qualification rate, alignment rate, and seedling tray placement efficiency. The results are shown in Table 5.

Table 5

ANOVA results

Sources of variance	Qualification rate of seedling tray spacing		Qualification rate of alignment		Efficiency of the seedling tray placement	
	Sum of squares	P-value	Sum of squares	P-value	Sum of squares	P-value
Model	205.06	<0.0001**	234.16	<0.0001**	62380.79	<0.0001**
X_1	2.28	0.0122*	12.78	<0.0001**	2358.04	<0.0001**
X_2	24.23	<0.0001**	4.03	0.0005**	1736.54	<0.0001**
X_3	36.41	<0.0001**	25.32	<0.0001**	49431.45	<0.0001**
X_1X_2	0.3486	0.2761	0.6105	0.0974*	98.00	0.1133
X_1X_3	6.50	<0.0003**	1.39	0.0185*	200.00	0.0306*
X_2X_3	3.14	0.0046**	0.6216	0.0947	18.00	0.4797
X_1^2	88.26	<0.0001**	89.87	<0.0001**	5222.33	<0.0001**
X_2^2	15.31	<0.0001**	56.57	<0.0001**	1477.79	<0.0001**
X_3^2	30.07	<0.0001**	45.51	<0.0001**	1942.99	<0.0001**
Residual error	3.51		2.49		441.82	
Lack of fit	1.37	0.4631	1.39	0.1808	134.26	0.6399
Error	2.14		1.10		307.56	
Sum total	208.56		236.65		62822.61	

Note: '*' denotes a significant difference (P < 0.05), while '**' denotes a highly significant difference (P < 0.01). The same applies below.

The experimental data were analyzed using Design Expert 13 software to perform analysis of variance (ANOVA), allowing identification of the factors with the most significant influence. Based on this, regression equations between the performance indicators and the coded factor values were established.

$$\begin{cases} Y_1 = 96.18 + 0.41X_1 - 1.33X_2 - 1.63X_3 + 0.90X_1X_3 - 0.63X_2X_3 - 2.36X_1^2 - 0.98X_2^2 - 1.38X_3^2 \\ Y_2 = 96.24 + 0.97X_1 - 0.54X_2 - 1.36X_3 + 0.42X_1X_3 - 2.38X_1^2 - 1.89X_2^2 - 1.69X_3^2 \\ Y_3 = 716.19 + 13.14X_1 + 11.28X_2 + 60.16X_3 - 5.00X_1X_3 - 18.13X_1^2 - 9.64X_2^2 - 11.06X_3^2 \end{cases} \quad (17)$$

Response surface analysis

To analyze the relationship between the test indexes and the factors more intuitively, the response surface of the factors' interaction with the test indexes was obtained using Design-Expert 13 software, as shown in Fig. 12.

Fig. 12(a) illustrates the effects of the horizontal inclination angle of the sliding plate and the pusher speed on the passing rate of rice seedling tray spacing. Overall, the passing rate remains relatively stable and consistently high. However, as both the horizontal inclination angle and the pusher speed increase, the passing rate gradually declines. This trend can be attributed to the influence of the tilt angle on the tray's orientation during landing and the pusher speed on its vertical velocity. Both factors affect the placement accuracy and alignment of the seedling trays, leading to decreased spacing uniformity and thus a lower passing rate.

Fig. 12(b) shows the influence of the horizontal inclination angle of the tilting frame and the pusher speed on the alignment qualification rate of the seedling trays. When the pusher speed is held constant, increasing the tilting frame inclination angle initially improves the alignment qualification rate, but further increases lead to a decline. In contrast, when the tilting frame inclination is fixed, increasing the pusher speed results in a continuous decrease in the alignment qualification rate. This indicates that pusher speed has a more significant effect on alignment accuracy compared to the tilting frame angle.

Fig. 12(c) illustrates the effects of the horizontal inclination angle of the tilting frame and the pusher speed on the tray placement efficiency. As both the inclination angle and pusher speed increase, the efficiency of the tray placement process also improves. Among the two factors, the pusher speed has a more pronounced influence on overall efficiency. In general, high placement efficiency is observed when the pusher speed is within the range of 0.16~0.22 m/s and the horizontal inclination angle is between 12° and 18°.

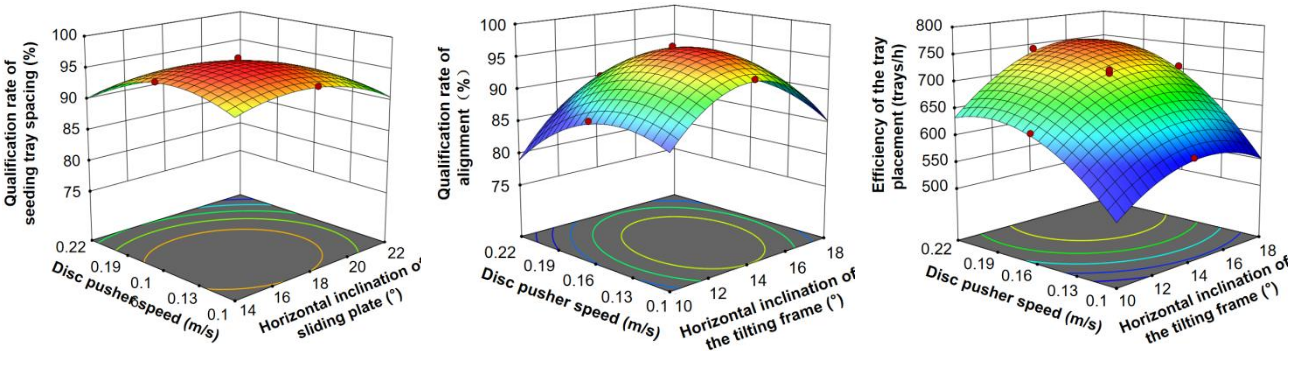


Fig. 12 – Response surface of the interaction effect of test factors on the qualified rate of seedling tray spacing

Optimization of parameter combinations

To obtain the optimal parameter combination of the tray placement machine, the multi-objective parameter optimization algorithm in Design Expert 13 software was used to optimize the experimental design, establish a parametric mathematical model, and combine the boundary conditions of the experimental factors, thereby improving the overall operational quality of the machine. The objective function is:

$$\begin{cases} \max y_1(X_1, \ X_2, \ X_3) \\ \max y_2(X_1, \ X_2, \ X_3) \\ \max y_3(X_1, \ X_2, \ X_3) \\ \text{s.t.}\begin{cases} -1.682 \le X_1 \le 1.682 \\ -1.682 \le X_2 \le 1.682 \\ -1.682 \le X_3 \le 1.682 \end{cases} \end{cases} \tag{18}$$

Using the multi-objective parameter optimization module in Design-Expert 13 software to analyze and solve the objective function, the optimal operating parameters for the seedling tray placement machine were determined. Optimal performance is achieved when the horizontal inclination angle of the tilting frame is 15°, the horizontal inclination angle of the sliding plate is 18°, and the pushing speed of the seedling tray pusher is 0.16 m/s. Under these conditions, the qualification rate for tray spacing reaches 96.25%, the qualification rate for alignment is 96.16%, and the tray placement efficiency is 722 seedling trays per hour.

Field test results

To verify the optimal parameter combination of the seedling tray placement machine, multiple field validation tests were conducted, and the results were processed and analyzed. The machine was tested under the optimized conditions: a horizontal inclination angle of the tilting frame set to 15°, a horizontal inclination angle of the sliding plate set to 18°, and a pusher speed of 0.16 m/s. Under these conditions, the average qualification rate for tray spacing was 96.11%, the alignment qualification rate was 95.89%, and the tray placement efficiency reached 714 trays per hour. The mean error between the simulation and field results was less than 1%, indicating that the optimization model is reliable. A comparison of the simulation results and field test results is provided in Table 6.

Table 6

Comparison test results

Type	Qualification rate of seedling tray spacing Y_1/(%)	Qualification rate of alignment Y_2/(%)	Efficiency of seedling tray placement Y_3/(trays/h)
simulation test	96.25	96.16	722
field test	96.11	95.89	714

CONCLUSIONS

1) To address the problem of height disparity between the output device of the tray placement machine and the seedbed in the enclosed stacked-tray seedling cultivation mode, which leads to vibration and displacement of the seedling trays during landing, an output device with buffering capability was designed. This structure ensures that the seedling trays are placed smoothly and accurately, improving overall placement quality.

2) Field validation tests showed that under the optimized operating parameters - 15° horizontal inclination angle of the tilting frame, 18° horizontal inclination angle of the sliding plate, and 0.16 m/s pusher speed - the qualification rate for tray spacing was 96.11%, the alignment qualification rate was 95.89%, and the tray placement efficiency reached 714 trays per hour. These results are largely consistent with the simulation predictions, confirming the reliability of the optimization model.

3) The developed automatic seedling tray placement machine for multi-row rigid rice seedling trays is controlled via a PLC system, which enables fully automated tray conveying and placement. The system ensures high efficiency and standardized operation, while the precise alignment of trays minimizes greenhouse space waste and reduces production costs for farmers.

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