RESEARCH AND VALIDATION OF AN OPTIMIZED DESIGN METHOD FOR GUIDE TUBES BASED ON THE STEEPEST DESCENT CURVE
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基于最速降线的导种管优化设计方法研究与验证

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ABSTRACT
The accuracy of seed placement is critical for achieving uniform plant spacing in the field. During seeding operations, the final seed placement is influenced by multiple factors. Irregular bouncing and rolling caused by seeds colliding with the walls of the seed guide tube during discharge is a key factor leading to low seeding uniformity. To investigate the optimal structural parameters and operational parameter ranges for the seed movement constraint device designed in this study, a kinematic analysis of its operational process was conducted. This analysis evaluated the device's operational effectiveness and the uniformity of seed placement. A multi-factor experiment was designed using central composite design and seed placement/posture detection technology. The experimental factors included buffer plate length, horizontal installation position of the guide plate, and working speed of the seed distributor. The experimental indicators were pass rate and coefficient of variation. Experimental results were processed and optimized using Design Expert-13 software. The most ideal combination was determined to be: a buffer plate length of 87.55 mm, and a guide plate horizontal installation position of 22.57 mm. At these settings, seed placement uniformity and stability were optimal, with a seed placement qualification index of 93.431% and a coefficient of variation of 9.324%. This confirms the rationality of the designed seed movement restraint device.

摘要
播种作业过程中，种子的最终落种位置受到多种因素的综合影响，投种过程中种子与导种管壁弹跳产生的不规则碰撞引起的弹跳是导致播种平稳性低的关键影响因素。为了探究本课题设计的种子运动约束装置最优结构参数与工作参数组合范围，对种子运动约束装置的工作过程进行了运动学分析，分析种子运动约束装置的作业效果以及种子的落种均匀性。通过中心组合试验和落点落姿检测技术设计多因素试验，以缓冲挡板的长度、引导板水平安装位置以及排种器的工作转速作为试验因素，以合格指数和变异系数作为试验指标，运用 Design Expert-13 软件对实验结果进行处理优化，得到在机具前进速度为 5.72km/h、缓冲挡板长度为 87.55mm 和引导板水平安装位置为 22.57mm 时，落种均匀性及稳定性最佳，此时播种合格指数和变异系数分别为 93.431%和 9.324%，由此得出所设计种子运动约束装置合理。

INTRODUCTION
Achieving uniform seeding with a planter is crucial for high corn yields. Within complex mechanical structures, the design of the seed delivery tube significantly impacts the precision of corn seed placement and overall seeding effectiveness *(Li et al., 2023)*. Consequently, scholars worldwide have conducted in-depth research on improving seed delivery tube designs. Existing mechanical seeders primarily employ a two-stage “straight-curved” seed tube configuration. Theoretical analysis establishes the horizontal velocity equation at the seed tube outlet, enabling structural optimization based on the zero-velocity seeding principle *(Wang et al., 2025)*. For large-seeded crops like corn, which require constraints during placement to control multidirectional movement, experts worldwide have extensively studied seed dynamics, necessary constraints, and constraint-providing mechanisms. Research indicates external constraints must be applied during corn seed placement to prevent irregular collisions with the planter, which exacerbate bouncing and rolling after soil contact *(Wang et al., 2021 and Gao et al., 2016)*. ENDRERUD employed numerical simulation to analyze seed tube-implement combinations, investigating how seed kinetic energy loss during descent is influenced by tube dimensions and mounting conditions.

Results indicate that beyond a certain tilt angle, seed tube size has negligible impact on kinetic energy loss during seed movement *(Endrerud et al., 1999)*. When the seed guide tube consists of an inclined plane section and an arc curve section, the kinetic energy loss of seeds within the tube is minimized. This research provides theoretical support for optimizing seed guide tubes based on the brachistochrone principle. Sun addressed the challenge that existing seed guide devices struggle to meet the high-speed operation demands of corn triangular dense-planting seed. Based on the brachistochrone principle, they designed an air-assisted guide-channel type seed guide device. The seed guide tube curve was optimized based on the principle of the line of least descent under friction considerations, yielding its profile equation *(Sun et al., 2025)*. Zubrilina employed kinematic analysis to examine seed velocity and angle at the seed tube outlet, establishing its motion profile to enhance post-tube seed distribution uniformity *(Zubriling et al., 2017)*. Wang Muchuan et al. designed a seed tube optimized for finger-type seeders to improve sub-supersonic operation efficiency and quality, validating the optimized seed delivery curve through discrete element simulation *(Wang et al., 2025)*. Wang Jinwu et al. investigated the grain transport patterns in finger-type corn seeders to enhance seed delivery performance. They established kinematic and dynamic models of the seed delivery process, analyzing how various factors influence transport stability and seed placement trajectories *(Wang et al., 2017)*. Li Peize et al. analyzed the forces acting on corn seeds within the seed distributor and seed guide tube. They proposed a precise prediction kinetic model for seed placement location. Results demonstrated the model's effectiveness in accurately forecasting seed placement positions *(Li et al., 2024)*. Li Jiajun et al. addressed the seed guide tube selection issue for finger-type seeders in sub-high-speed corn planters operating at 8–12 km/h. Focusing on angle variations, they conducted high-speed camera bench tests. Results revealed severe seed bouncing in 16° guide tubes *(Li et al., 2024)*. Scholar Yang Wencai improved the traditional straight-section seed delivery tube into a dual-section design based on zero-speed seeding theory. This tube, composed of a straight segment and a curved segment, was configured for the 2BQ 28 precision seed drill for Panax notoginseng. It resolved issues of uneven and unstable seeding *(Yang et al., 2017)*. As summarized from the above literature, theoretical research on seed-guiding technology by scholars both domestically and internationally primarily focuses on analyzing the movement process of seeds within seed-guiding devices. During their studies, researchers employed various methods to examine the effects of factors such as the shape and height of the seed-guiding device, seeding operation speed, and seed distributor rotational speed on seeding uniformity. Comparative analysis of results from different methodologies has validated the rationality of seed-guiding device research. Due to variations in metering unit structures and seed deposition trajectories, seed guide devices exhibit distinct characteristics. Based on the external constraints applied to seeds during deposition, existing seed guide devices can be categorized into three types: unconstrained, under-constrained, and fully-constrained *(Liao et al., 2024)*. Unconstrained devices cause seeds to bounce and roll after soil contact; under-constrained devices reduce post-contact bounce displacement; fully constrained devices eliminate irregular collisions between seeds and the guide, significantly improving sowing uniformity, though they require complex guide systems *(Du et al., 2017)*. Therefore, this research group selected the finger-clamp seed feeder (as shown in Figure 1) combined with a seed guide tube featuring a seed restraint mechanism. The restraint mechanism within the guide tube primarily consists of a buffer plate and a buffer guide plate. The main function of these components is to reduce unpredictable bouncing of seeds as they enter the straight section of the guide tube, ensuring seeds enter the curved section with minimal initial velocity and maximum precision.

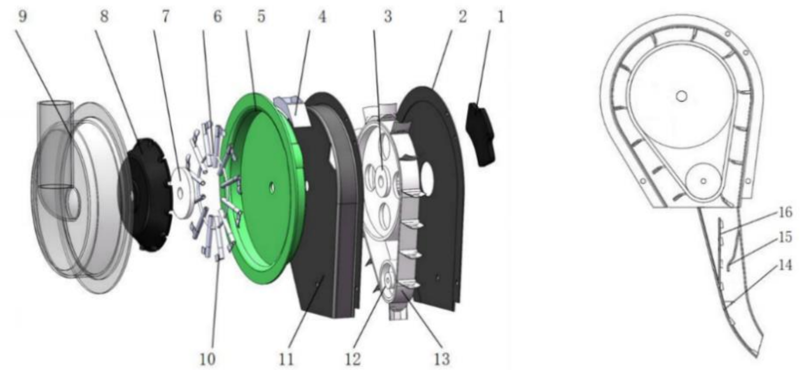


Fig. 1 – A seed tube equipped with a restraint device

1-Seeder Inspection Pane; 2-Seed Guide Cover; 3-Seed Guide Pulley; 4-Pure-Bristle Brush; 5-Seed Tray; 6-Tuning Spring; 7-Cam; 8-Finger-grip clamping disc; 9-Seed-filling cap; 10-Seed-retrieval finger grip; 11-Seed-guiding end cap; 12-Seed-guiding pulley; 13-Seed-guiding belt; 14-Seed Guide Tube; 15-Buffer Guide Plate;16-Buffer Baffle

The linear motion state of seeds entering the seed guide tube via the seed distributor, along with the initial velocity, exit velocity, and slip time during the curved segment, directly impact the precision delivery performance of the finger-clamp type seed distributor. To optimize the curved section of the seed guide tube design, this study will conduct a kinematic analysis of the seed descent process based on the theory of the line of least descent and the energy conservation equation *(Golubev et al., 2013)*. It will also account for the work done by the seed's friction resistance along the main curve to establish a mathematical model for the curved section. To better align with practical conditions, this paper will employ landing point and posture detection technology for bench testing to validate the structural rationality *(Zhao et al., 2025)*.

MATERIALS AND METHODS

Seed Kinematic Analysis

To ensure corn seeds glide smoothly through the seed chute and settle into the seedbed, the design of the seed restraint device should focus on analyzing the seeds' motion state and velocity before entering the brachistochrone phase, as well as their trajectory during the gliding phase. The objectives are to minimize unpredictable bouncing during the straight section of the chute, reduce the duration of the gliding phase, and balance the relative velocity in the machine's forward direction. Based on this research, a kinematic analysis of the seed's trajectory within the seed tube will be conducted to derive the equation of the line of least descent under the seed movement restraint device. During operation of the finger-clamp seed dispenser, seeds pass through the designed restraint device to smoothly enter the initial position M of the straight section at minimum velocity. They then rapidly and stably slide along the brachistochrone path to the seeding point N. Based on the actual sliding process of the seeds, Figure 2 is the force diagram.

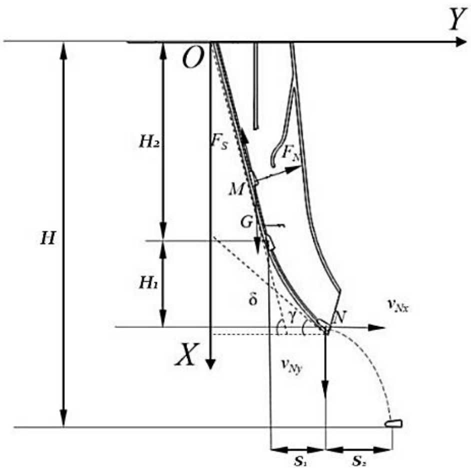


Fig. 2 – Kinematics Analysis Diagram of Seed Guide Constraint Device

The meanings of the parameters in the figure are shown in Table 1.

Table 1

Meaning of Parameters in Force Diagram

Parameter Name	Parameter Explanation
F_N	Seed-supporting force of the seed guide tube
F_S	Friction between the seed tube and the seed
G	Seed self-gravity
H	Vertical height of seed tube installation position from ground level
H_1	Vertical Height of Curved Section of Seed Guide Tube
H_2	Vertical Height of Straight Section of Seed Guide Tube
S_1	Horizontal distance from the curve segment's entrance to its exit
S_2	Horizontal distance from the curve segment exit to the planting ground position

With the pipe opening connecting the seed guide tube to the seed distributor as the origin O of the coordinate system, the direction opposite to the machine's forward movement as the positive direction of the X-axis, and the vertical downward direction as the positive direction of the Y-axis, a plane rectangular coordinate system is established. The force relationship acting on the seed along the inclined straight segment is as follows:

$$\begin{cases} F_N = mg\cos\gamma \\ F_{S1} = \mu F_N \end{cases} \tag{1}$$

Based on the line of least descent theory, this curved segment is simplified into a parabola passing through the origin, with its equation set as $y = ax^2 + b$ *(Chen et al., 2019)*. At this stage, the seed slides down the curved pipe under its own gravity. Upon entering the discharge section, its initial velocity is the terminal velocity from the inclined straight segment. To analyze the seed's motion, the following force equation is established:

$$m\frac{dv}{dt} = mg\frac{dy}{ds} - \mu mg\frac{dx}{ds} \tag{2}$$

From the above equation, the velocity of the seed upon leaving the steepest descent segment is:

$$v_N = \sqrt{v_M^2 + 2g(y - \mu x)} \tag{3}$$

in the formula: v_N — speed of corn seeds upon leaving the delivery section, [m/s];
v_M— speed of corn seeds upon entering the braking section, [m/s];
X, Y — horizontal and vertical distances of the braking section, [mm];

When the seed completes its sliding motion from the starting point M along the steepest descent line to the delivery point N, the sliding height of the corn seed in the coordinate system is H_1. The work done by the frictional force acting on the corn seed at this point is denoted as W_f, expressed as:

$$W_f = \int F_S ds == \int_{x_M}^{\frac{-b+\sqrt{b^2+4aH_1}}{2a}} mg\tan\varphi\, dx = mg\tan\varphi\left(\frac{-b+\sqrt{b^2+4aH_1}}{2a} - x_M\right) \tag{4}$$

The motion state of corn seeds during the steepest descent phase is related to their vertical displacement, initial velocity, and final velocity during the sliding process. Furthermore, their movement within the seed chute adheres to the law of conservation of energy:

$$\frac{1}{2}mv_N^2 + mgH_1 = mg\tan\varphi\left(\frac{-b+\sqrt{b^2+4aH_1}}{2a} - x_M\right) + \frac{1}{2}mv_M^2 \tag{5}$$

Combining and simplifying equations (1) to (5) yields:

$$W_f = \frac{v_M^2 - v_N^2 - 2g(y-\mu x) + 2gH_1}{2g\tan\varphi} \tag{6}$$

Among them: $b = (y_M - ax^2)/x_M$,obtain:

$$a = \frac{2H_1x_M - 2Ay_M - 3x_My_M}{2x_M^3 + 4A^2x_M^2 + 2A^2x_M} \tag{7}$$

$$A = \frac{v_M^2 - v_N^2 + 2gH_1}{2g\tan\varphi} \tag{8}$$

Substituting the above parameters into the steepest descent curve equation yields:

$$y = \left(\frac{2H_1x_M - 2Ay_M - 3x_My_M}{2x_M^3 + 4A^2x_M^2 + 2A^2x_M}\right)x^2 + bx \tag{9}$$

The theoretical analysis above indicates that the seed movement curve design within the seed delivery tube must accommodate varying seeding speeds. According to relevant literature, the speed combination that minimizes corn seed bounce displacement upon soil contact is: 0.51 meters per second tangential velocity when the corn seed contacts the soil, and a normal relative velocity of 1.08 m/s at the moment of soil contact. Common seeders operate at speeds of 4–8 km/h. Under these conditions, the measured rotational speed of the finger-type precision corn seeder ranges from 15 to 45 r/min *(Liu et al., 2017)*. With the seeder installed at a height of 220 mm on the planter and the vertical height of the designed steepest descent phase set at 100 mm, the lateral distance of point N from the origin is 95.31 mm. Substituting the above data into (9) yields the equation for the line of maximum descent of the seed guide tube with a seed movement constraint device:

$$y = 0.05 + 0.47x \tag{10}$$

Experimental Bench Assembly and Design Plan

To comprehensively investigate the performance variation patterns of the seed motion control device under different operating conditions, analyze the key factors affecting its operational uniformity and stability, and subsequently determine the optimal parameter combination, a high-speed photography test apparatus was designed, as shown in Figure 3.

This apparatus employs a Thousand-Eyed Wolf landing point and attitude detector to capture parameters such as seed displacement, velocity, angle, and motion trajectory within the seed guide tube. It determines the relationship between the initial collision position of seeds in a standard guide tube and the travel speed, while also validating the applicability of the designed seed restraint device and the rationality of the calculated steepest descent line based on experimental data.

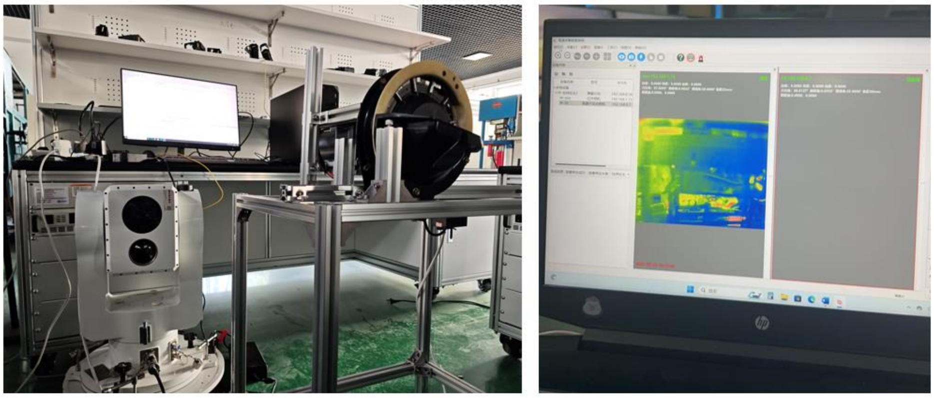


Fig. 3 – High-Speed Photography Analysis System for Landing Point and Landing Posture with Test Bench

Based on the analysis of the landing posture test rig conditions, Figure 4 shows that the initial impact points for corn seeds in standard seed tubes all occur on the straight section. As the vehicle speed increases, a small number of seeds may directly reach the curved section and bounce out of the seed tube. The seed restraint device constrains the descent of corn seeds along the straight section, forcing them to follow a constrained path and steadily enter the curved section's inlet before sliding out through the seed discharge port.

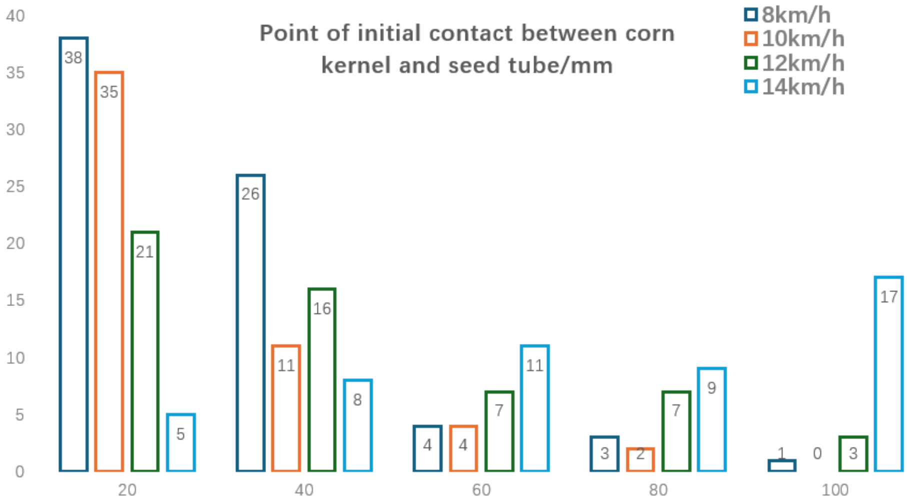


Fig. 4 – Distribution Map of First Impact Locations for Corn Kernels

Through preliminary theoretical analysis and discussion of the data from the aforementioned high-speed photography experiments on landing points and postures. During the operation of the finger-type seed dispenser, corn seeds are guided by the seed conveyor belt to the seeding position before being ejected from the dispenser. As the row-cutting speed increases during seeding, the collision point of the seeds shifts downward, intensifying the drift phenomenon in the seeding trajectory. This leads to uncontrollable collisions between seeds and the seed-guiding mechanism, severely compromising the uniformity of plant spacing. The primary function of the precision placement plate is to ensure that corn seeds are delivered into the seed furrow at the most consistent position possible, thereby improving the uniformity of seed placement. These include the forward speed of the implement, the length of the precision seeding plate, and the installation position of the precision seeding plate. Through comprehensive analysis of these factors, the range of levels for each factor was determined, and levels for each factor in the testing were set, as table 2 shows:

Table 2

Performance Testing Level and Factors Table for Motion Restraint Devices

Level	Experimental factors		
	Forward speed of machinery	Buffer pad length	Installation Location of Cushion Pad
-1	4	50	15
0	6	75	20
1	8	100	25

To quantitatively evaluate the operational effectiveness of the designed seed movement control device, reference was made to two standards: the national standard GB/T6973-2005 "Experiment Methods for Single-Seed Planters" and the industry standard JB/T10293-2001 "Technical Specifications for Single-Seed Planters." In this experiment, the pass index and coefficient of variation were selected as key evaluation metrics. The coefficient of variation primarily measures operational stability, while the pass index assesses the overall uniformity of the seed feeder and seed motion control device. Their respective calculation formulas are:

$$S = \frac{n_0}{N} \times 100\% \quad (11)$$

In the formula: S - qualification Index, [%];

n_0- single-seed row spacing, [particle];

N- theoretical Seeding Rate, [particle].

$$C = \sqrt{\frac{\sum(x-\Delta x)}{(n-1)\Delta x^2}} \times 100\% \quad (12)$$

In the formula: C- Coefficient of Variation, [%];

n- Total Number of Sample Granules, [particle];

x- Theoretical Seeding Spacing, [mm];

Δx- Average grain size of the sample, [mm].

RESULTS

This study employed a three-factor, three-level central composite design to optimize the multi-factor seeding process and measure multiple seed spacing groups as shown in Figure 5.

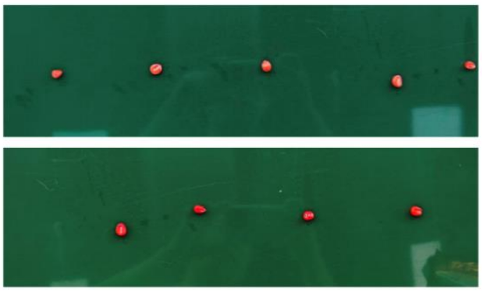


Fig. 5 – Measurement and Statistics of Single-Seed Planting Spacing for Corn

During the experiment, significance analysis was conducted on key factors influencing evaluation metrics. To obtain more precise data, the coordinate information of corn seeds transported stably along the seed delivery tube was continuously recorded throughout the experiment. The specific experimental design and experimental data are output in table 3.

Table 3

Performance Testing Level and Factors Table for Motion Restraint Devices

Serial Number	Experimental factors			Performance Metrics	
	x_1	x_2	x_3	S	C
	[km/h]	[mm]	[mm]	[%]	[%]
1	4	50	20	84.79	11.11
2	8	50	20	89.77	10.17
3	4	100	20	91.08	9.97
4	8	100	20	87.91	10.73

Serial Number	Experimental factors			Performance Metrics	
	x_1	x_2	x_3	S	C
	[km/h]	[mm]	[mm]	[%]	[%]
5	4	75	15	92.19	9.69
6	8	75	15	88.01	10.56
7	4	75	25	90.31	9.85
8	8	75	25	84.79	11.11
9	6	50	15	91.58	9.74
10	6	50	15	83.65	11.26
11	6	100	25	89.86	9.98
12	6	50	25	87.13	10.79
13	6	75	20	90.25	9.88
14	6	75	20	92.37	9.85
15	6	75	20	85.65	11.03
16	6	75	20	82.59	11.33
17	6	75	20	89.57	10.37

Based on these experiments, regression analysis was performed on the relevant experimental data using Design Expert-13 software to identify factors significantly influencing the results, as shown in Tables 4 and 5. Regression equations were obtained for the pass rate index, coefficient of variation, and each factor. Here, x_1, x_2, and x_3 represent the forward speed of the implement, the length of the precision seeding plate, and the installation position of the precision seeding plate, respectively. S and C denote the experimental data for the pass index and coefficient of variation, respectively.

Table 4

Analysis of variance of seed spacing qualification index

Sources of variance	Sum of Squares	Degrees of freedom	Mean Square	F	p
Model	150.93	9	16.77	148.99	<0.0001
A	22.14	1	22.14	196.74	<0.0001
B	0.7875	1	0.7875	7.00	0.0332
C	91.53	1	91.53	813.19	<0.0001
AB	0.3844	1	0.3844	3.42	0.1071
AC	2.64	1	2.64	23.46	0.0019
BC	0.0156	1	0.0156	0.1388	0.7205
A^2	17.89	1	17.89	158.90	<0.0001
B^2	13.66	1	13.66	121.34	<0.0001
C^2	0.6787	1	0.6787	6.03	0.0437
Residuals	0.7879	7	0.1126		
misspelling items	0.3834	3	0.1278	1.26	0.3991
errors	0.4045	4	0.1011		
sum	151.72	16			

Table 5

Analysis of variance of coefficient of variation for seed spacing

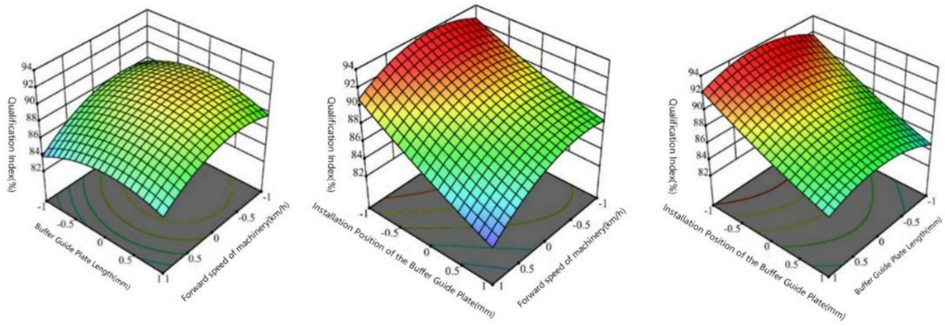
Sources of variance	Sum of Squares	Degrees of freedom	Mean Square	F	p
Model	6.00	9	0.6663	153.65	<0.0001
A	0.4278	1	0.4278	98.66	<0.0001
B	0.0024	1	0.0024	0.5650	0.4768
C	3.74	1	3.74	862.49	<0.0001
AB	0.289	1	0.289	6.66	0.0364
AC	0.210	1	0.210	4.85	0.0636

Sources of variance	Sum of Squares	Degrees of freedom	Mean Square	F	p
BC	0.0004	1	0.0004	0.922	0.7702
A^2	0.8068	1	0.8068	186.06	<0.0001
B^2	0.8726	1	0.8726	201.24	<0.0001
C^2	0.0251	1	0.0251	5.79	0.0470
Residuals	0.0304	7	0.0043		
misspelling items	0.0105	3	0.0035	0.7025	0.5981
errors	0.0199	4	0.0050		

$$S = 89.95 - 1.66x_1 + 0.3138x_2 - 3.38x_3 - 0.815x_1x_3 - 2.06{x_1}^2 - 1.8{x_2}^2 + 0.4015{x_3}^2 \quad (13)$$

$$C = 10.01 + 0.2312x_1 + 0.6837x_3 - 0.85x_1x_2 + 0.4378{x_1}^2 + 0.4553{x_2}^2 - 0.0773{x_3}^2 \quad (14)$$

Based on the preceding analysis, response surface plots for each factor and the two indicators were generated using Design-Expert-13 software *(Cui et al., 2010)*, as shown in Figures 6 and 7. These response surfaces visually illustrate the relationships between each indicator and the factors, as well as the interactions among the factors *(Liu et al., 2017 and Yang et al., 2010)*. Under the premise of ensuring precision seeding and maintaining smooth seed sliding within the seed motion control device, an in-depth analysis of the influence patterns of each factor was conducted. As shown in Figure 6(a), an interaction exists between the forward speed of the implement and the length of the precision seeding plate. When the fixed seed placement plate position is fixed, the combined effect of forward speed and fixed seed placement plate length on the qualification index manifests as follows: at a constant forward speed, increasing the fixed seed placement plate length causes the qualification index to rise initially and then decline, with a relatively gradual trend. Conversely, at a constant fixed seed placement plate length, increasing the forward speed causes the qualification index to decrease, initially at a slow rate and then rapidly. As shown in Figure 6(b), there is an interaction between the forward speed of the implement and the mounting position of the precision seeding plate. When the length of the precision seeding plate is fixed, the combined effect of the implement's forward speed and the installation position of the precision seeding plate on the qualification index manifests as follows: at a constant forward speed, the qualification index decreases sharply with increasing distance of the precision seeding plate installation position. Conversely, at a constant installation position, the qualification index first decreases slowly and then rapidly as the forward speed increases.



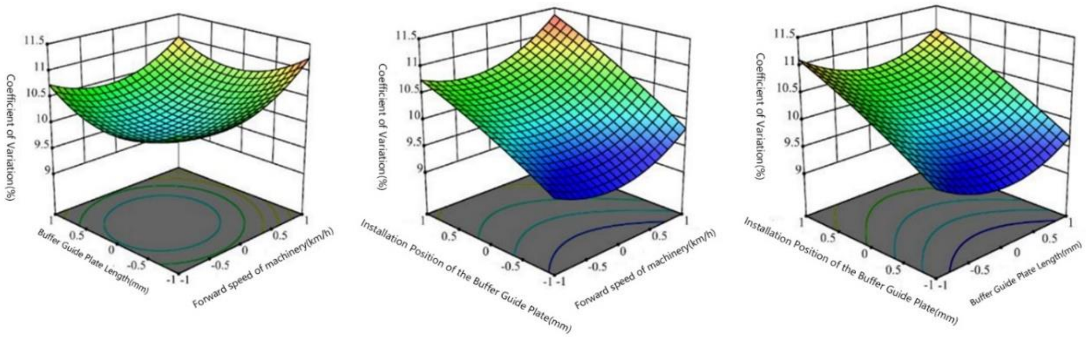
a) b) c)

Fig. 6 – Impact of Factors on the Qualification Index

a-Impact of Factors x_1x_2; b-Impact of Factors x_1x_3;
c-Impact of Factors x_2x_3

As shown in Figure 6(c), there is an interaction between the length of the precision seeding plate and its mounting position. At a constant implement forward speed, the combined effect of precision seeding plate length and mounting position on the qualification index manifests as follows: when the precision seeding plate length is at a certain level, the qualification index shows a decreasing trend as the mounting distance increases, with a relatively sharp change. When the precision seeding plate mounting position is at a certain level, the qualification index first increases and then decreases as the precision seeding plate length increases, with a relatively gradual change. In summary, the factors affecting the qualification index in order of significance are the installation position of the precision seeding plate, the forward speed of the implement, and the length of the precision seeding plate.

As shown in Figure 7(a), there is an interaction between the forward speed of the implement and the length of the precision seeding plate. When the fixed seed placement plate position is fixed, the combined effect of machine forward speed and fixed seed placement plate length on the coefficient of variation manifests as follows: at a constant machine forward speed, the coefficient of variation first decreases slowly and then increases slowly as the fixed seed placement plate length increases. Conversely, at a constant fixed seed placement plate length, the coefficient of variation first decreases and then increases as the machine forward speed increases, with both trends being relatively gradual. As shown in Figure 7(b), the travel speed of the implement and the mounting position of the seeding plate influence each other. When the length of the precision seeding plate is fixed, the combined effect of implement forward speed and mounting position on the coefficient of variation manifests as follows: at a constant implement forward speed, the coefficient of variation decreases sharply as the mounting distance increases. When the fixed seeding plate position is fixed, as driving speed increases, the coefficient of variation first decreases and then increases, with a relatively gradual trend. As shown in Figure 7(c), there is an interaction between the length of the fixed seeding plate and its mounting position. At a constant implement forward speed, the combined effect of precision seeding plate length and installation position on the coefficient of variation manifests as follows: When the precision seeding plate length is at a certain level, as the installation distance increases, the coefficient of variation shows a decreasing trend, with a relatively sharp change; when the precision seeding plate installation position is at a certain level, as the length of the precision seeding plate increases, the coefficient of variation first decreases and then increases, with a relatively slow change. In summary, the factors affecting the coefficient of variation in order of significance are: the installation position of the precision seeding plate, the forward speed of the implement, and the length of the precision seeding plate. By analyzing the response surfaces for each factor's impact on the pass rate and coefficient of variation, the order of significance affecting seeding performance is determined as follows: the installation position of the precision seeding plate has the greatest impact, followed by travel speed of agricultural implements, with the length of the precision seeding plate having the least impact.



a) b) c)

Fig. 7 – The Impact of Factors on the Coefficient of Variation

a) Impact of factors x_1x_2; b) Impact of factors x_1x_3; c) Impact of factors x_2x_3

Based on this, Design-Expert-13 software was employed to perform an optimal solution search for the parameters to achieve the best combination of qualified index and coefficient of variation. Seeding operations can be performed at higher speeds and enhance the overall operational quality of the equipment, a parametric mathematical model was constructed by integrating the boundary conditions of each experimental factor. The objective function and constraints were selected as follows:

$$\begin{cases} maxS \\ minC \\ s.t\begin{cases} 4 \ll x_1 \ll 8 \ [km/h] \\ 50 \ll x_2 \ll 100 \ [mm] \\ 15 \ll x_3 \ll 25 \ [mm] \\ 0 < S(x_1,x_2,x_3) \ll 1 \\ 0 < C(x_1,x_2,x_3) \ll 1 \end{cases} \end{cases} \tag{15}$$

Working speed range of agricultural implements was selected as 4 km/h to 8 km/h, the length range of the precision seeding plate as 50 mm to 100 mm, and the installation position range of the precision seeding plate as 15 mm to 25 mm. Optimization was performed to maximize the qualification index and minimize the coefficient of variation. The optimal conditions were determined to be a machine speed of 5.72 km/h, a precision seeding plate length of 87.55 mm, and a precision seeding plate mounting position of 22.57 mm.

At these settings, seeding uniformity and stability were optimal, with a qualification index of 93.431% and a coefficient of variation of 9.324%.

CONCLUSIONS

To evaluate the operational effectiveness and seed distribution uniformity of the seed motion control device, this study employed discrete element simulations to analyze its working process. The influences of multiple factors on device performance were examined, and the optimal structural and operational parameters were determined. These results provide theoretical support for prototype development, bench testing, and subsequent field trials.

Geometric models of the seed distributor and the seed motion control device were established, and their motions were defined according to actual working conditions. A three-factor, three-level Box-Behnken experimental design was conducted, using the qualified index and coefficient of variation as evaluation metrics. The experimental factors included machine forward speed, precision seeding plate length, and precision seeding plate mounting position. This approach enabled the determination of optimal structural and working parameters for the seed motion control device.

The virtual simulation results showed that optimal seeding performance was achieved at a forward speed of 5.72 km/h, a precision seeding plate length of 87.55 mm, and a precision seeding plate mounting position of 22.57 mm. Under these conditions, the qualified index reached 93.431%, while the coefficient of variation was 9.324%.

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