DESIGN AND EXPERIMENTAL EVALUATION OF A HIGH-SPEED SPOON-BELT POTATO SEED-METERING DEVICE
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带勺式马铃薯高速排种装置设计与试验

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ABSTRACT
Aimed at mitigating the elevated leakage rate and multiple rate, as well as unstable plant spacing observed during high-speed (5–8 km/h) operation of potato planters, this study designs the key components of a spoon-type potato seed metering device. The primary configuration and operating principle of the metering device are presented, and the critical components involved in the metering process are subjected to theoretical analysis and structural design. To identify the optimum operating parameters, a three-factor, three-level orthogonal test was performed with seed belt linear speed, seed-spoon opening diameter, and seed-box inclination angle as experimental factors and leakage rate and multiple rate as evaluation indicators, thereby optimizing the high-speed potato seed metering device. The experimental results indicated that, at 5.38 km/h, the device performed best when the seed belt linear speed was 0.42 m/s, the seed-spoon opening diameter was 58.34 mm, and the seed-box inclination angle was 10°, resulting in a leakage rate of 3.68% and a multiple rate of 4.07%.The comparison experiments demonstrated that, at 5.38 km/h, the curved guide plate decreased the leakage rate by 1.31 percentage points, the multiple rate by 0.45 percentage points, and the plant-spacing coefficient of variation by 5.02 percentage points. Field experiments indicated that the high-speed potato seed metering device attained a leakage rate of 4.35%, a multiple rate of 4.72%, and a plant-spacing coefficient of variation of 13.51%, providing a basis for the optimization design of high-speed seed metering devices.

摘要
针对目前马铃薯播种机在5-8km/h高速作业情况时，存在漏重播率高、株距不稳定的问题，本文对带勺式马铃薯播种机排种装置关键部件进行设计。阐述了排种装置的主要结构和工作原理，对排种过程中关键部件进行了理论分析与结构设计。为研究排种装置的最佳工作参数，以排种带速度、种勺直径和种箱倾角为试验因素，漏播率和重播率为评价指标，开展三因素三水平正交试验，对马铃薯高速排种装置进行了参数优化设计。试验结果表明，在作业速度5.38km/h条件下，排种带速度为0.42 m/s，种勺直径为58.34mm，种箱倾角为10°，排种装置性能最优，漏播率为3.68%，重播率为4.07%。通过对比试验结果表明，在作业速度5.38km/h条件下，使用弧形导向板时，排种装置漏播率降低1.31个百分点，重播率降低了0.45个百分点，株距变异系数降低5.02个百分点。田间试验结果表明，马铃薯高速排种装置漏播率为4.35%，重播率为4.72%，株距变异系数为13.51%，研究结果可为高速排种装置优化设计提供参考。

INTRODUCTION
Potato is the fourth most important staple crop in China, following maize, wheat, and rice; in recent years, continued increases in planting area and total production have been accompanied by steadily rising market demand (*Pang et al., 2023; Zhou et al., 2025*). However, mechanized potato planting in China remains at a relatively low level, resulting in low operational efficiency and high labor inputs, which substantially constrains large-scale industrial development and constitutes a key bottleneck to improving production efficiency (*Lyu et al., 2015; Wang et al., 2022*). Therefore, the development of a high-speed seed-metering device tailored to potato production is of great significance for ensuring national food security and improving potato yield potential, and it has emerged as a major research focus in the advancement of planting technologies (*Tang et al., 2022*).

High-speed planting represents a critical technological component and an important agronomic requirement for achieving mechanized potato planting (*Sun et al., 2020; Tian et al., 2022; Li et al., 2024*). As the core component of a planter, the performance of the seed-metering device directly determines the quality of planting operations. Mechanical seed-metering systems widely used in potato planters can be broadly categorized into chain-spoon and spoon-belt types (*Li et al., 2025; Wang et al., 2024*). The chain-spoon mechanism provides a stable and reliable transmission ratio; however, at high operating speeds, periodic impacts during chain–sprocket engagement and disengagement readily excite vibrations in the drive chain, thereby degrading seed pickup accuracy (*Zhang et al., 2024; Li et al., 2024*). By contrast, the spoon-belt mechanism tends to maintain better performance under high-speed conditions; nevertheless, the irregular size distribution of cut seed tubers compromises the consistency of pickup and release, thereby increasing missing- and double-seeding. To date, studies on spoon-belt seed-metering devices remain relatively scarce, especially those focusing on metering performance under high-speed operating conditions, which is still in its infancy (*Zhang et al., 2020; Cujbescu et al., 2021*). Therefore, advanced approaches are required to further investigate and optimize the spoon-belt seed-metering system.

To enhance seed-metering performance, extensive research has been carried out worldwide to mitigate missing and double-seeding (*Voicu et al., 2014; Cujbescu et al., 2020*). Cai Haoxuan et al. conducted numerical simulations of the seed-spoon pickup process considering the irregular geometry and poor flowability of cut seed tubers, elucidated the mechanism for improving metering performance by incorporating an eccentric seed-lifting device, and determined the key influencing factors and the optimal parameter combination via DEM–MBD coupled simulations and bench experiments (*Cai et al., 2025*). Qian Guofeng et al. developed an eccentric embedded precision dibble seeder, established a dynamic model for the seed-filling process, investigated the effects of operating speed and brush extension length on missing- and double-seeding rates using a multi-factor rotational composite design, and validated the structural feasibility through bench experiments (*Ma et al., 2024*).

To tackle these issues, this paper focuses on a high-speed spoon-belt potato seed-metering device, investigates the force and kinematic characteristics of the metering process under high-speed operating conditions, designs and fabricates the device, and identifies the optimal combination of key parameters via a three-factor, three-level orthogonal design. The findings provide a theoretical basis for improving the efficiency and quality of high-speed potato seed metering, thereby facilitating precision planting under high-speed operating conditions.

MATERIALS AND METHODS

CONFIGURATION AND OPERATING PRINCIPLE OF THE SEED-METERING DEVICE

Configuration of the seed-metering device

As illustrated in Fig. 1, the seed metering device is primarily composed of the finger-type seed spoon, seed protection cover, drive shaft, vibratory seed-cleaning unit, driven pulley, seed-delivery belt, secondary seed hopper, seed-separating baffle, primary seed hopper, housing plate, drive pulley, and curved guide plate.

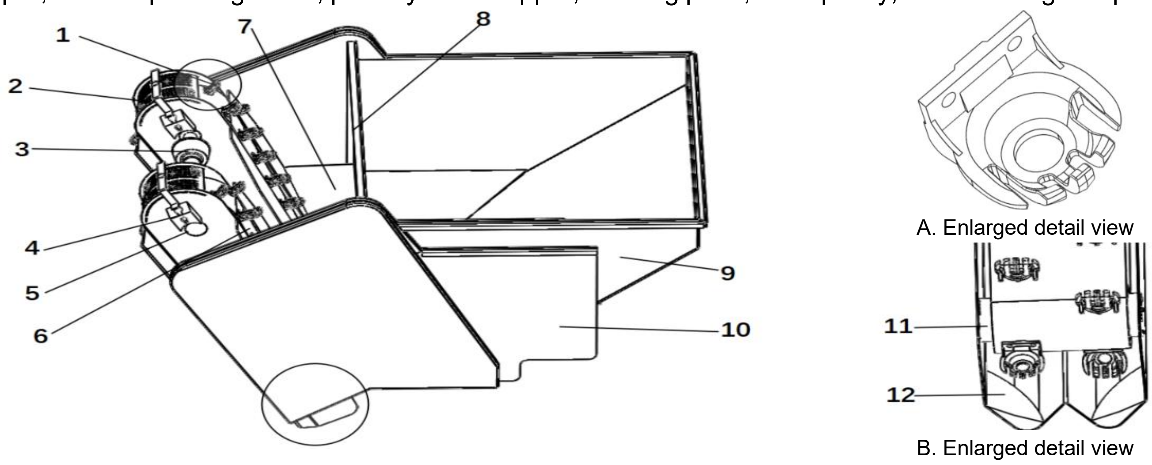


Fig. 1 –Schematic of the seed metering device structure

1 - Finger-type seed scoop; 2 - Protective housing for seed tubers; 3 - Transmission shaft; 4 - Vibration-based seed cleaning mechanism; 5 - Idler pulley; 6 - Seed-delivery belt; 7 - Secondary seed hopper; 8 - Partition baffle for seed separation; 9- Primary seed hopper; 10 - Housing plate; 11 – Drive pulley; 12 - Curved guide plate

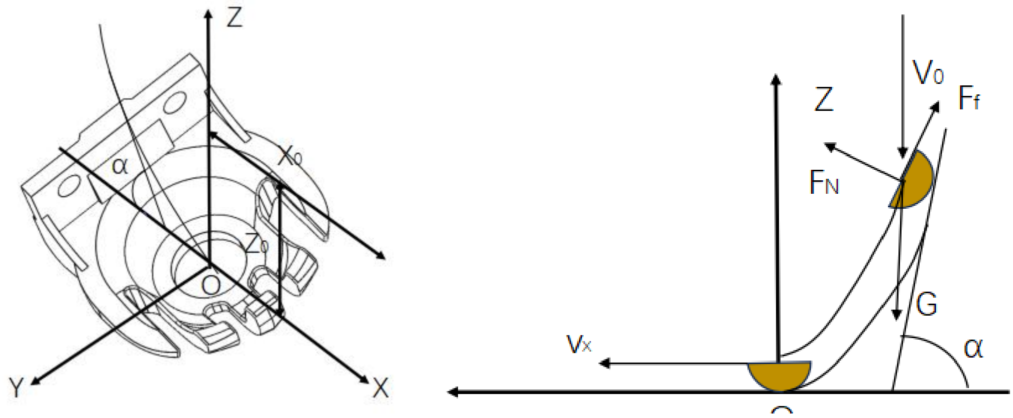
Working principle

During normal operation of the seed metering device, potato seed tubers are continuously replenished into the primary seed hopper under gravity, and then, driven by gravity and lateral pressure within the tuber mass, they slide along the sidewall into the secondary seed hopper; the baffle regulates the tuber layer height to adjust flow behavior and suppress arching. In the seed-filling stage, the finger-type seed spoon located in the filling region travels with the seed-delivery belt and picks up one or more seed tubers from the tuber bed to complete seed filling. The seed-delivery belt is driven by a motor, and the motor torque is transferred via the transmission mechanism to the driving pulley; the driving pulley then rotates the driven pulley, thus driving the seed-delivery belt together with the finger-type seed spoon to travel steadily upward from bottom to top. During seed clearing, the vibratory seed-cleaning unit is in contact with the seed-delivery belt; by tuning the vibration frequency, surplus tubers in the finger-type seed spoon are dislodged to complete seed clearing. After the clearing zone, the tuber retained in the spoon falls under gravity onto the back of the previous pickup spoon, forming a closed cavity with the seed-guiding cover to complete the seed-guiding process. During seed discharge, the curved guide plate on both sides of the outlet converges and guides the tuber flow, causing the two tuber rows to drop to the ridge center upon release, thereby realizing approximately zero-speed placement and completing the discharge process.

KEY COMPONENT DESIGN AND ANALYSIS

Finger-type seed spoon

The finger-type seed spoon is the key functional component of the seed-metering device, and its geometric configuration and associated parameters directly influence pickup performance, filling stability, and seed-tuber damage (*Zhaomei et al., 2023*). In the spoon design, it is necessary to ensure reliable scooping of seed tubers and a near-balanced force state of the tuber within the spoon, thereby improving filling stability and reducing the filling time (Fig. 2a). This study applies brachistochrone theory to analyze and optimize the spoon's internal profile, minimizing—under high-speed operating conditions—the time required for a seed tuber to slide from an upper point to a lower point along a cycloidal path, thereby reducing missing- and double-seeding while maintaining a high single-tuber rate.



(a) Finger- type seed spoon *(b) analysis of the cycloidal cut-off line*

Fig. 2 –Schematic of the finger-type seed spoon

Design rationale

In the Central Plains double-cropping region, potato planting commonly uses cut seed tubers; nevertheless, the wide variability in piece geometry and the limited controllability of cutting patterns make it difficult to establish unified definitions for key parameters of cut seed pieces. Therefore, to enhance the adaptability of the finger-type seed spoon, the potato cultivar "Xisen 7" was selected, and seed tubers were processed in accordance with relevant national standards for seed-tuber preparation in the Central Plains double-cropping region: each tuber was spiral-cut obliquely toward the apical end along its longitudinal axis and then sectioned into 2–4 pieces according to the apical-bud distribution, ensuring that each seed piece contained 1–2 intact eyes and its mass was maintained within 25–30 g (*Wouwer et al., 2025*). The geometric dimensions (length, width, and thickness) of the cut seed pieces were measured using a vernier caliper; 100 pieces were randomly sampled per run, measurements were replicated three times, and the mean of the three datasets was used as the final value set (Table 1).

Table 1

Statistical summary of potato seed tuber size distribution

Replication count	Length, mm	Width, mm	Thickness, mm
Trial 1	54.16	43.91	30.21
Trial 2	57.64	42.67	35.89
Trial 3	52.81	48.34	34.26
Mean	54.87	44.97	33.45

Considering the size parameters of the cut seed pieces in Table 1, the finger-type seed spoon should be designed to satisfy geometric matching and kinematic constraints while minimizing spoon–tuber impact and contact pressure during metering, thereby achieving the combined requirements of single-piece pickup, stable tuber posture, and low damage.

Optimization of the spoon body

To enhance seed filling and mitigate the multiple rate and leakage rate, this study examines the tautochrone (isochronous) profile of the finger-type seed spoon, aiming to minimize the descent time of Potato seed tubers from the upper to the lower position along a cycloid; the kinematic schematic of the finger-type seed spoon is shown in Fig. 2b. With the bottom of the finger-type seed spoon defined as the origin O, a three-dimensional coordinate system O-xyz is constructed; adopting a parametric representation, the ideal sliding path of Potato seed tubers is assumed to be a cycloid, and the corresponding parametric equations are as follows:

$$\begin{cases} z_0 = r(1-cos\theta_0) \\ x_0 = r(\theta_0 - \sin\theta_0) \end{cases} \tag{1}$$

where:

z_0 – vertical coordinate of the seed tuber along the cycloidal path, [m];

x_0 - horizontal coordinate of the seed tuber along the cycloidal path, [m];

r - radius of the cycloid's generating circle, [m];

θ_0 - parameter angle of the cycloid, [°].

As the seed piece slides to the bottom of the seed spoon, the cross-sectional profile becomes cycloidal, and the work of the friction force W_f can be written as:

$$W_f = -\int_{x_0}^{0} \mu mgdx = -mg\tan\varphi x_0 \tag{2}$$

By applying energy conservation, it follows that:

$$\frac{1}{2}mv_0^2 + mgz_0 = -mg\tan\varphi x_0 + \frac{1}{2}mv^2 \tag{3}$$

where:

m - mass of the potato seed tuber, [g];

φ - angle of friction between the cut seed piece and the seed spoon, [°];

G - acceleration due to gravity, [m/s^2];

v_0 - initial velocity of the cut potato seed piece, [m/s];

v - terminal horizontal velocity of the cut potato seed piece, [m/s];

a - angle between the cut-off line and the tangent at the sliding point, [°].

Combining and simplifying Eqs. (1)–(3) yields a transcendental equation for θ_0.

$$\frac{1-\cos\theta_0}{\theta_0 - \sin\theta_0} = \tan\varphi - \frac{v_0^2}{2gx_0} \tag{4}$$

where α denotes the tangent inclination angle, given by:

$$\alpha = \arctan(\frac{\sin\theta_0}{1-\cos\theta_0}) \tag{5}$$

In the ideal case, the seed-piece velocity at the spoon bottom is set to 0 m/s, and the friction angle φ between the seed piece and the seed spoon is 24°–39°; by substituting these parameters into Eq. (3), the tangent inclination angle α is obtained as 29.8°–52.4°.

Speed-matching analysis of the seed metering belt

As a critical component of the seed metering device, the seed-delivery belt links the finger-type seed spoon to carry out seeding, as illustrated in Fig. 3. Ideally, the number of finger-type seed spoon passing a given point per unit time on the seed-delivery belt equals the discharge count of the seed metering device; thus, the discharge frequency is governed by the seed belt linear speed together with the spoon pitch. Since the discharge frequency must be coordinated with the machine forward speed to achieve the desired plant spacing, the seed belt linear speed governs both the spatial layout and discharge cadence of the finger-type seed spoon and is therefore strongly coupled to the planter travel speed.

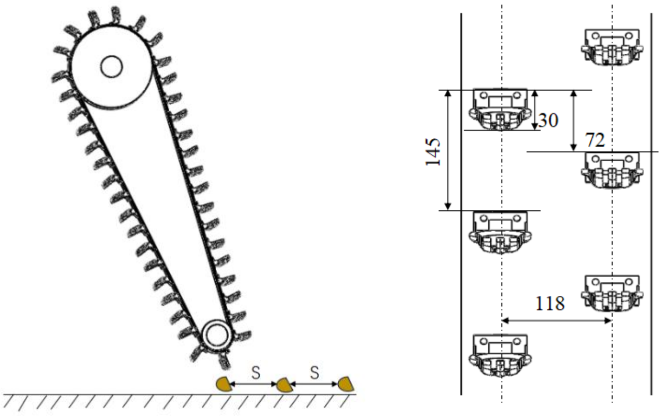


Fig. 3 – Schematic of the seed metering belt arrangement and motion analysis

To examine the kinematic behavior of the seed-delivery belt in the high-speed potato seed metering device and meet agronomic plant-spacing requirements, it is necessary to derive a kinematic expression for the seed belt linear speed, namely:

$$V_1 = \frac{\pi D_1 N}{60} \tag{6}$$

$$\frac{V_2 t}{S} = \frac{V_1 t}{L} \tag{7}$$

$$k = \frac{D_2}{D_1} \tag{8}$$

where:

V_1 - Seed-metering belt speed, [m/s];
N - Rotational speed of the pulley, [r/min];
D_1 - Driving-pulley diameter, [mm];
V_2 - Forward travel speed of the implement, [m/s];
S - Potato in-row plant spacing, [mm];
L - Inter-spoon spacing of the finger-type seed spoons, [mm];
D_2 - Driven-pulley diameter, [mm].

With reference to the agronomic requirements for high-speed potato planting in the Central Plains double-cropping region, when the planter forward speed is 5–8 km/h and the target in-row spacing is 250 mm, and the driving and driven pulley diameters are 80 mm and 35 mm, respectively, the corresponding metering-belt speed is 0.40–0.56 m/s, satisfying the agronomic requirements for high-speed planting.

Traditional potato planters commonly employ ground-wheel drive, whereby the rotation of the ground-contact wheel powers the planter's working components. At high operating speeds, this drive mode is susceptible to accuracy degradation and performance variability, which in turn compromises planting quality. Therefore, a motor-driven metering belt is adopted in this study to enable precision planting under high-speed operating conditions.

Seed hopper design

Owing to the irregular dimensions and diverse shapes of cut potato seed tubers, a single seed-box configuration is susceptible to arching blockage, uneven feeding, and increased tuber damage. Accordingly, the seed box is designed as a combined primary seed hopper–secondary seed hopper structure, with a seed-separating baffle installed between them to buffer and divert the tuber flow, thereby enhancing feeding continuity and stability (*Wu et al., 2024*).

In the dual-hopper system, the primary seed hopper has a larger volume and primarily serves for tuber storage and feeding; tubers descend along the inner wall under gravity together with lateral pressure in the tuber mass. A portion of the tubers is held in the upper region of the primary seed hopper by the baffle, whereas the rest is diverted into the secondary seed hopper to work with the pickup spoon for tuber pickup. Meanwhile, as tubers reach the junction of the primary seed hopper and secondary seed hopper, the resistance increases, making tuber buildup more likely. The seed-box inclination angle directly governs how smoothly tubers enter the pickup spoon; increasing the inclination promotes tuber descent into the secondary seed hopper under gravity and lateral pressure, enhancing tuber–spoon contact and improving pick up.

Nevertheless, an overly large inclination angle decreases the effective seed-box volume and tends to cause tuber accumulation at the bottom, thereby hindering pickup. Accordingly, to maintain adequate flowability of Potato seed tubers within the seed box and ensure stable pickup, the seed-box capacity and the seed-box inclination angle must be appropriately designed.

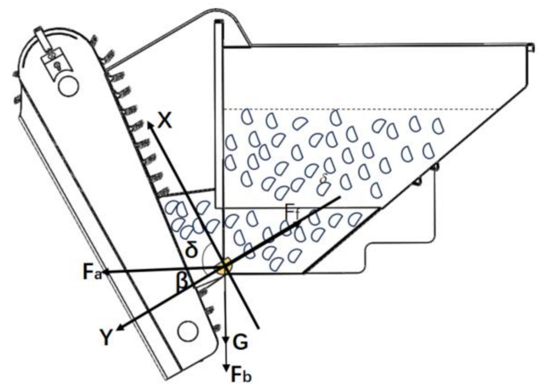


Fig. 4 – Force analysis of seed tubers within the primary and secondary hoppers

To ensure adequate flowability of seed pieces within the seed box, a force analysis was performed. The junction between the main and auxiliary chambers was taken as the origin O, and a two-dimensional coordinate system O–xy was defined, with the x-axis normal to the inclined surface of the main chamber and the y-axis tangential (parallel) to it. As illustrated in the figure, the following relationships can be derived:

$$\begin{cases} (G+F_b)\cos\delta + F_a\sin\delta > F_f \\ F_f = \mu(N + F_a\cos\delta) \\ N = (G+F_b)\sin\delta \end{cases} \tag{9}$$

where:

G - Gravity (self-weight) of the seed-piece bulk, [N];

F_a - Lateral pressure between seed pieces in the bulk, [N];

F_b - Longitudinal pressure between seed pieces in the bulk, [N];

F_f - Friction force acting on the seed-piece bulk, [N];

Δ - Complement of the seed-piece inclination angle, [°].

The mixed potato seed bulk was idealized as a two-dimensional homogeneous continuum, and the self-weight (overburden) stress theory from engineering geology was applied; the resulting longitudinal and lateral pressures can be expressed as:

$$\begin{cases} F_a = \dfrac{\mu_a}{1-\mu_a}\gamma hA \\ F_b = \gamma hA \end{cases} \tag{10}$$

By rearranging Eqs. (9)–(10), the following relationship is obtained:

$$\delta = arc\tan\left(\frac{\mu F_a - (G+F_b)}{F_a - \mu(G+F_b)}\right) \tag{11}$$

Therefore, the seed-box inclination angle β should satisfy:

$$\beta < \frac{\pi}{2} - arc\tan\left(\frac{\mu F_a - (G+F_b)}{F_a - \mu(G+F_b)}\right) \tag{12}$$

The seed-box volume is calculated as

$$V = \frac{1.1LBN_{max}}{10000\gamma} \tag{13}$$

where:

μ_a - Friction coefficient between the seed piece and the seed-box sidewall;
Υ - Bulk density of the seed-piece bulk, [N/m³];
H - Bulk height of seed pieces in the seed box, [m];
A - Wall-projected contact area of the seed-piece bulk, [m²];
B - Inclination angle of the seed box, [°];
M - Friction coefficient between the seed pieces and the bottom of the seed box;
V - Required effective capacity of the seed box, [m³];
L - Length of the field plot, [m];
B - Effective operating width of the machine, [m];
N_{max} - Maximum planting amount, [kg/hm²].

In summary, to meet the agronomic requirement of at least one round trip, L was set to 400 m, giving a required seed-box volume of 160 L; to prevent remaining seed pieces at the box bottom, the seed-box volume was selected as 200 L. Among them, the friction coefficient between the seed pieces and the bottom of the seed box is 0.49, the friction coefficient between the seed pieces and the seed-box sidewall is 0.33, the bulk density of the seed-piece bulk is 5.4–6.4 × 10³ N/m³, the bulk height of seed pieces in the seed box is 0.5–0.8 m, the wall-projected contact area of the seed-piece bulk is 0.15–0.25 m², and the gravity (self-weight) of the seed-piece bulk is 554.5–3653.4 N. Due to the considerable variation in the upper and lower bounds of these parameters, in order to reflect the effect of different working conditions on the stress state, the upper and lower limits of each parameter were combined and substituted into Equation (12), yielding a seed-box inclination angle β of 9.98°–24.31°.

TEST-BENCH EXPERIMENT

Experimental conditions

To optimize the parameter combination of seed belt linear speed, seed-box inclination angle, and seed-spoon opening diameter and achieve optimal operating performance, a bench test was performed on September 12, 2025 at the Hongzhu Potato Experimental Base in Jiaozhou, Shandong Province. The experimental setup included a high-speed potato seed metering unit, a small belt conveyor, a 550 W brushless DC motor, a driver, and a switching power supply; by regulating motor speed, the conveyor speed was adjusted to emulate the planter travel speed, ensuring experimental feasibility, as shown in Figure 5.

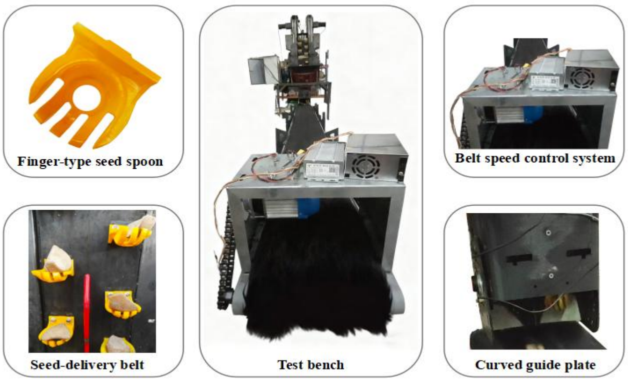


Fig. 5 –Test apparatus

Experimental design

Building on the above analysis, to improve the operating performance and reliability of the high-speed potato seed metering device, seed belt linear speed (X_1), seed-spoon opening diameter (X_2), and seed-box inclination angle (X_3) were chosen as test factors, while leakage rate (Y_1) and multiple rate (Y_2) were used as metering performance indicators; a three-factor, three-level experiment was implemented, and the factor coding is given in Table 2.

Table 2

Experimental factor coding

Encodings	seed belt linear speed, X_1 (m/s)	Seed-spoon opening diameter, X_2 (mm)	seed-box inclination angle, X_3 (°)
a	0.40	55	10
b	0.48	60	15
c	0.56	65	20

In accordance with agronomic requirements for potato planting and referring to GB/T 6973—2005 Test methods for single-seed (precision) planters, potato leakage rate Y_1 (%) and multiple rate Y_2 (%) were used as evaluation indicators; in each run, 100 potato seed tubers stably discharged by the metering unit were counted, and the formulas for these indices are given in Eqs. (14–15).

$$Y_1 = \frac{n_1}{N_0} \times 100\% \tag{14}$$

$$Y_2 = \frac{n_2}{N_0} \times 100\% \tag{15}$$

where:

N_0 - Theoretical seeding count;

n_1 - Count of missed seed pieces;

n_2 - Count of seeding events with ≥2 seed pieces.

RESULTS AND DISCUSSION

Experimental results and ANOVA

The experimental design and results are presented in Table 3, where X_1, X_2, and X_3 denote the coded levels of the factors. The experimental data were subjected to analysis of variance (ANOVA) using Design-Expert 13.0; the results are reported in Tables 4 and 5 and were used to assess the significance of factor effects on the response indices.

Table 3

Test design and results

Standards	Experimental factor			Performance indicator	
	X_1	X_2	X_3	Y_1	Y_2
1	0	0	0	6.62	4.72
2	-1	0	1	5.40	7.46
3	0	1	-1	3.41	5.57
4	0	-1	1	8.35	4.43
5	-1	-1	0	7.50	6.33
6	1	-1	0	10.63	3.44
7	1	1	0	7.87	4.33
8	1	0	-1	8.01	3.03
9	0	0	0	6.60	4.74
10	0	1	1	6.07	6.00
11	0	0	0	6.61	4.84
12	-1	1	0	4.63	8.90
13	1	0	1	9.13	4.02
14	0	-1	-1	7.40	2.75
15	0	0	0	6.03	4.48
16	-1	0	-1	3.77	5.97
17	0	0	0	6.55	4.97

As indicated in Tables 4 and 5, the regression models for missing- and double-seeding rates were highly significant ($P<0.01$), whereas the lack-of-fit tests were not significant ($P>0.05$), demonstrating that the developed models achieved a satisfactory fit. The significance analysis indicated that, for the missing-seeding model, the linear effects of metering-belt speed (X_1), seed-box inclination angle (X_2), and seed-spoon diameter (X_3) were highly significant, and the interaction term $X_1 \times X_2$ was significant, whereas the remaining terms were not significant; for the double-seeding model, the linear terms X1 and X_2 and the quadratic terms X_1^2, X_2^2, and X_3^2 were highly significant, while the linear term X_3 and the interaction term $X_1 \times X_2$ were significant, and all other terms were not significant.

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Table 4

Analysis of variance for the leakage rate

Source	Sum of squares	Freedom	Mean of squares	F-value	P-value	Significance
Model	53.81	9	5.98	57.98	< 0.0001	Significant
A	25.70	1	25.70	249.24	< 0.0001	
B	17.70	1	17.71	171.64	< 0.0001	
C	5.06	1	5.06	49.03	0.0002	
AB	0.0030	1	0.0027	0.0258	0.8689	
AC	0.0650	1	0.0642	0.6305	0.4532	

Source	Sum of squares	Freedom	Mean of squares	F-value	P-value	Significance
BC	0.7310	1	0.7282	7.09	0.0324	
A^2	2.20	1	2.20	21.33	0.0024	
B^2	0.8631	1	0.8599	8.37	0.0232	
C^2	1.66	1	1.66	16.06	0.0051	
Residual	0.7219	7	0.1036			
Lack of fit	0.4636	3	0.1556	2.39	0.2091	Insignificant
Pure Error	0.2583	4	0.0646			
Cor Total	54.54	16				

Table 5

Analysis of variance for the multiple rate

Source	Sum of squares	Freedom	Mean of squares	F-value	P-value	Significance
Model	38.39	9	4.27	74.39	< 0.0001	Significant
A	23.94	1	23.94	417.52	< 0.0001	
B	7.70	1	7.70	134.32	< 0.0001	
C	2.63	1	2.63	45.92	0.0003	
AB	0.7056	1	0.7056	12.30	0.0099	
AC	0.0625	1	0.0622	1.09	0.3312	
BC	0.3906	1	0.3906	6.81	0.0349	
A^2	2.16	1	2.16	37.67	0.0005	
B^2	0.3390	1	0.3390	5.91	0.0453	
C^2	0.5048	1	0.5048	8.80	0.0209	
Residual	0.4014	7	0.0573			
Lack of fit	0.2710	3	0.0903	2.77	0.1749	Insignificant
Pure Error	0.1304	4	0.0326			
Cor Total	38.79	16				

After screening, a multivariate quadratic regression model retaining only the highly significant and significant terms was established as follows:

$$Y_1 = 6.48 + 1.79X_1 - 1.49X_2 + 0.79X_3 + 0.43X_2X_3 + 0.72X_1^2 + 0.45X_2^2 - 0.63X_3^2 \quad (16)$$

$$Y_2 = 4.75 - 1.73X_1 + 0.98X_2 + 0.57X_3 - 0.42X_1X_2 + 0.71X_1^2 + 0.28X_2^2 - 0.34X_3^2 \quad (17)$$

Response surface methodology (RSM) analysis

To visualize the relationships between the response indices and the factors, response surface plots were generated in Design-Expert 13.0, as shown in the figures.

Fig. 6 shows the response surface of the leakage rate. Fig. 6 indicates that the leakage rate rises with seed belt linear speed, declines as seed-spoon opening diameter increases, and shows a slight increase with seed-box inclination angle.

Fig. 7 presents the response surface of the multiple rate. According to Fig. 7, the multiple rate decreases as seed belt linear speed increases, but increases with both seed-spoon opening diameter and seed-box inclination angle.

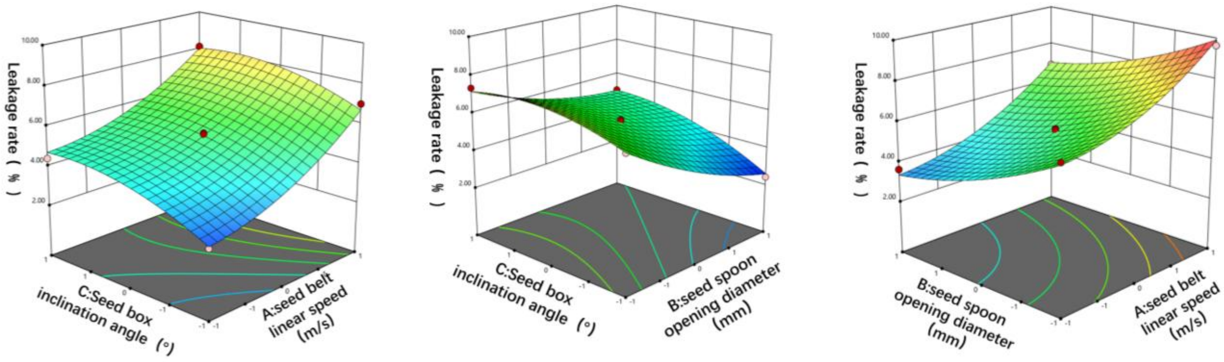

Fig. 6 – Response surface showing the effect of factor interactions on the leakage rate

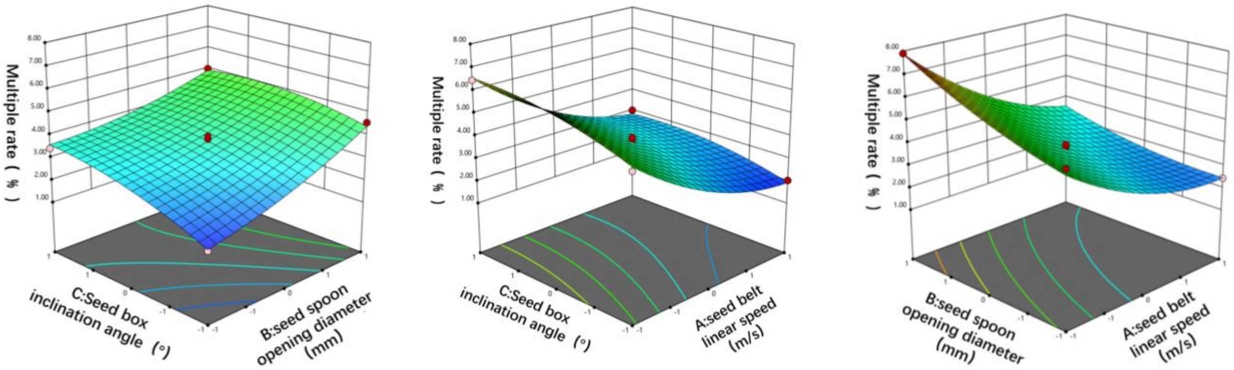

Fig. 7 – Response surface showing the effect of factor interactions on the multiple rate

Parameter optimization and validation experiment

Optimization was performed using the parameter optimization module in Design-Expert 13.0 to determine the optimal parameter combination. The objective function and constraints were established as follows:

$$\begin{cases} \min Y_1(X_1, X_2, X_3) \\ \min Y_2(X_1, X_2, X_3) \\ s.t. \quad \begin{cases} -1 \le X_1 \le 1 \\ -1 \le X_2 \le 1 \\ -1 \le X_3 \le 1 \end{cases} \end{cases} \tag{18}$$

To maintain low potato leakage rate and multiple rate under relatively high forward-speed conditions. Optimization of the above indices yielded the optimal combination: seed belt linear speed of 0.42 m/s, seed-spoon opening diameter of 58.34 mm, and seed-box inclination angle of 10°, resulting in a leakage rate of 3.68% and a multiple rate of 4.07% for the high-speed potato seed metering device.

At the optimal parameter combination, the seed belt linear speed was 0.42 m s^{-1}. According to the seed belt speed matching equation (6–8) derived above, when the forward speed of the potato planter was 5.38 km/h, a reasonable matching relationship between the seed belt motion and the machine forward motion was achieved, thereby resulting in the optimal operating performance of the high-speed potato seed-metering device.

To validate the performance improvement provided by the curved guide plate, five repeated tests were performed at 5.38 km/h, comparing metering performance with and without the curved guide plate; the results are presented in Table 6.

Table 6

Experimental factor coding

Seed metering device structure	Leakage rate (%)	Multiple rate (%)	Plant spacing coefficient of variation (%)
No guide plate	4.76	4.35	17.32
Guide plate installed	3.45	3.94	12.30

The comparison tests indicated that, at 5.38 km/h, the seed metering device lacking the curved guide plate exhibited increases of 1.31 percentage points in the leakage rate, 0.45 percentage points in the multiple rate, and 5.02 percentage points in the plant spacing coefficient of variation. Fig. 8 shows the comparison of performance before and after optimization of the device.

(a) Prior to optimization of the device

(b) After optimization of the device

Fig. 8 - Comparison of seeding outcomes before and after optimization of the device

Field trial

To validate the applicability of the optimal condition identified in the bench tests under practical field operation, field trials were carried out on October 17, 2025, at the HongZhu Potato Experimental Base, Jiaozhou, Shandong, China. The test scenario is illustrated in Fig. 9.

Fig. 9 – Field planting experiment

The potato cultivar at the experimental site was "Xisen 7"; the test unit was a Hongzhu electric-driven potato planter powered by a Dongfanghong LX1304 tractor (96.2 kW), in which the original seed metering device was partially replaced by the high-speed potato seed metering device developed in this work with a curved guide plate.

To minimize experimental error, the test field was shallow-tilled prior to the trials. During operation, the mean forward speed was maintained at 5.38 km/h with a deviation within ±0.2 km/h. A two-row planting configuration was used; five replicate runs were performed under this condition, and the reported results are the average values, the results are presented in Table 7.

Table 7

Statistical summary of seed potato size distribution

Group ID	Leakage rate (%)	Multiple rate (%)	Plant spacing coefficient of variation (%)
1	4.12	4.51	12.98
2	4.56	4.86	11.42
3	4.41	4.79	13.87
4	4.29	4.65	13.65
5	4.37	4.79	15.63

Table 7 indicates that the high-speed potato seed metering device yielded an average leakage rate of 4.35%, an average multiple rate of 4.72%, and a plant spacing coefficient of variation of 13.51%. Because of the complex field environment and fluctuations in tractor travel speed, the indices increased slightly relative to ideal conditions; however, they remained stable within the error range (*Xu et al., 2025*).

Relative to the parameter-optimized bench tests, the average leakage rate, average multiple rate, and plant spacing coefficient of variation increased by 0.67, 0.62, and 1.21 percentage points, respectively, while the overall metering performance still satisfied agronomic requirements for potato planting.

CONCLUSIONS

To solve the elevated leakage rate and multiple rate observed in the high-speed potato seed metering device under high-speed conditions, this study designed a high-speed potato seed metering device and optimized key components, namely the finger-type seed spoon, seed-delivery belt, and seed box, thereby enhancing high-speed metering performance.

A three-factor, three-level experiment was conducted to develop a regression model relating metering performance to seed belt linear speed, seed-box inclination angle, and seed-spoon opening diameter; optimization of the parameter combination indicated that the optimal operating conditions of the seed metering device were seed belt linear speed of 0.42 m/s, seed-spoon opening diameter of 58.34 mm, and seed-box inclination angle of 10°. The resulting leakage rate and multiple rate were 3.68% and 4.07%, respectively.

Bench comparative results indicated that, at 5.38 km/h, incorporating the curved guide plate decreased the leakage rate, multiple rate, and plant spacing coefficient of variation by 1.31, 0.45, and 5.02 percentage points, respectively.

Field validation under the optimal parameter settings showed that, at 5.38 km/h, the developed high-speed potato seed metering device obtained an average leakage rate of 4.35%, an average multiple rate of 4.72%, and a plant spacing coefficient of variation of 13.51%, which complies with applicable standards for high-speed potato sowing.

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