DESIGN AND EXPERIMENTAL OF A SEED METERING DEVICE FOR SMALL SIZED VEGETABLE SEEDS
/
小粒径蔬菜种子排种器的设计与试验

Qichao LI*, Guoqin XU, Jinlong FENG
College of Mechanical and Electrical, Lingnan Normal University, Cunjin Street, Zhanjiang 524048, China
E-mail: qc_lee@126.com (correspondent author)
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ABSTRACT
To address the seeding difficulty and low precision of small sized vegetable seeds, a new precision seed metering device with separated seed picking and dropping functions was developed. The structure and working principle of the device were analyzed. The mass, three-axis dimensions, and angle of repose of three cabbage seed varieties were measured to analyze the statistical patterns of their orientation distribution. The structural parameters of key components including the seed picking wheel, seed dropping wheel, and separator plate were designed using numerical calculation methods. Bench performance tests were conducted for parameter optimization. The experiment adopted a quadratic orthogonal rotation composite design, with the working speed and tilt angle of the measuring device as experimental factors, and the qualified seed spacing index and coefficient of variation as evaluation indicators. The results indicated that when the working speed was 0.40-0.63 r/s and the tilt angle was 5.32-9.67°, the seeding qualified index can exceed 90% and the variation coefficient was smaller than 12%, meeting the requirements of good seeding standards. This study used a separated harvesting vegetable seed metering device to sow small vegetable seeds, providing a new concept and theoretical reference for precision vegetable seed metering devices.

中文摘要
针对小粒径蔬菜种子播种难度大，精度低等问题，研制一种新型取投分离式小粒径蔬菜种子精密排种器，分析排种器的结构和工作原理。分别测试三种甘蓝种子质量、三轴尺寸和自然休止角，并分析了姿态分布规律，利用数值计算方法，设计了取种轮盘、投种轮盘、分隔板等关键部件结构参数。通过台架性能试验进行参数优选，以排种器工作转速和倾斜角度为因素，播种粒距合格指数和变异系数为指标，采用多因素二次正交旋转组合设计试验。结果表明：排种器工作转速 0.40~0.63 r/min，倾斜角度 5.32~9.67°时，播种合格指数>90%，变异系数<12%，达到播种优等标准要求。该研究利用取投分离式排种器播种小粒径蔬菜种子，为蔬菜精密排种器的创制提供了新思路和理论参考。

INTRODUCTION
Vegetable production requires mechanization, and planting technology is a main link in mechanized vegetable production. Current vegetable planting methods are categorized into seedling transplanting and mechanical direct seeding *(Zamuco et al., 2023; Hensh et al., 2024; Sharma et al., 2024; Li et al., 2022; Sun et al., 2024)*. Seedling transplanting can effectively preserve seeds and control pests, diseases and weeds. However, the transplanting process is labor-intensive and the planting cost is high *(Paudel et al., 2024; Saqib et al., 2025; Liu et al., 2025)*. Mechanical direct seeding can simplify the transplanting process and reduce planting cost. Due to the small particle size and low mass of most vegetable seeds, the development of mechanical direct seeding technology is constrained *(Li and Feng, 2024; Sharaby et al., 2019; Sharma and Khar, 2024; Basit et al., 2021)*. The key component for vegetable seeding is the seed metering device. Its structure and working principle determine the seeding quality, directly affecting vegetable yield and quality *(Yang et al., 2024; Valentin et al., 2024)*.

Sharaby et al. (2022) predicted the outflow process of sesame seeds from the oscillating seed meter. The optimal values for the main parameters of the oscillating seed metering device for sowing sesame seeds are a seed hole clearance of 9 mm, an oscillation angle of 20°, and an opening time of 0.022 s, and a sesame seed rate of 2.7 kg/ha. This provides a reference for the design and optimization of oscillating seeders for small seeds.

Qichao LI, Associate professor, Ph.D.; Guoqin XU, Undergraduate student; Jinlong FENG, Associate professor, Ph.D.

Hensh and Raheman (2022) designed an electromagnetic driven seeder driven by a push-pull solenoid valve. The seeds are transported through a rectangular hole wheel disc and thrown out at the outlet to improve seeding accuracy. *Valentin et al. (2023)* developed a carrot seeder that uses a cylindrical component as seed metering device. The seeder precisely places seeds into hills at a uniform interval along a straight row over the plant bed. *Patel et al. (2024)* developed a radish pneumatic planter. The parameters for variables nozzle hole were designed, and the operating parameters including forward speed, vacuum pressure, and nozzle hole diameter were optimized to achieve the desired performance of the planter. *Kus and Yildirim (2021)* designed a slotted wheel seeder device. Through optimizing the design of the slotted wheel, the damage to the seeder was reduced. *Mintesinot and Khurana (2025)* designed a fluted roller-type metering devices with trapezoidal and asymmetric grooves, as well as an indented cell-type roller metering mechanism for berseem and lucerne crops. *Liao et al. (2024)* designed a roller-type precision seed metering device featuring device specifically for rapeseed, which combined positive-negative pressure and lateral seed filling. This design can reduce the pressure applied to the bottom seed mass in the filling zone, effectively preventing seed mass entrainment and accumulation.

These studies on vegetable seed metering devices mainly focused on the mechanism of a single seed disc with simultaneous seed picking and dropping operations. The devices that use two separate components for seed picking and seed dropping are limited. This separation method can directly implement two-stage seed filling and dropping processes in the device, thereby improving seeding precision. This study designed a precision seed metering device with separated picking and dropping functions for vegetable seeds. The structure and working principle of the device were analyzed, and structural parameters of its key components were optimized. This work can provide a theoretical foundation and a new concept for advancing vegetable seeding technology, and also provide an essential sowing machinery to support the mechanized production and large-scale cultivation of vegetables.

MATERIALS AND METHODS

Selection and Physical Properties of Tested Vegetable Seeds

The geometric properties of seeds determine their flow ability and seed filling performance within seeding devices, and are key references for designing key structural parameters of seed metering devices. Due to variations in the morphological characteristics of different seeds, the axial dimension method was used to measure the triaxial dimensions of three cabbage seed varieties to ensure seeding precision and broaden the applicable seeding range. The seed length (*l*), width (*w*), and thickness (*h*) were defined to represent their overall shape and size. In the experiment, three cabbage varieties: Zhonggan 21, Jingfeng 1, and Dongguan, suitable for cultivation in the Heilongjiang region were selected. One hundred seeds were randomly sampled from each variety for triaxial dimension measurement. The overall mean values and standard deviations were calculated, as shown in Table 1.

Table 1

Three-dimensional dimension of cabbage seeds

Varieties	Thousand kernel weight (g)	Length *L* (mm)	Standard deviation s(%)	Width *w* (mm)	Standard deviation (%)	Thickness *h* (mm)	Standard deviation (%)	Angle of repose *β*(°)
Zhonggan 21	3.59	1.72	0.13	1.68	0.15	1.22	0.08	25
Jingfeng 1	3.76	1.78	0.28	1.72	0.11	1.18	0.13	28
Dongguan	4.11	1.76	0.22	1.69	0.18	1.29	0.24	30

Table 2

Probability of postures of cabbage seeds in seed container

Varieties	Supine Orientation /%	Lateral Recumbent Orientation /%	Vertical Orientation /%
Zhonggan 21	41.06	29.82	29.12
Jingfeng 1	42.57	29.21	28.22
Dongguan	40.06	30.58	29.36

As shown in Table 2, the orientation distribution of the three types of tested seeds in the seed picking spoons showed that the supine orientation was the most common, accounting for over 40%. The lateral and vertical orientations were equivalent, each accounting for about 29%.

Structure Design of the Seed Metering Device

The structure of the separated picking and dropping vegetable seed metering device is shown in Fig. 1. It mainly consists of housing, seed picking wheel, separator plate, seed dropping wheel, metering shaft, seed cleaning brush, and end cover. The seed picking wheel, separator plate, and seed dropping wheel are sequentially mounted on the metering shaft with an axial clearance of 0.5 mm. The separation plate is rigidly fixed to the device housing. There are 12 evenly distributed seed picking spoons installed on the seed picking wheel, which correspond one-to-one with the 12 seed receiving units on the seed dropping wheel. The functional area for picking and dropping operations is physically isolated, achieving a series of functions such as seed collection and discharge. The seed cleaning brush is installed inside the end cover, and there is a threaded adjustment mechanism on the brush holder.

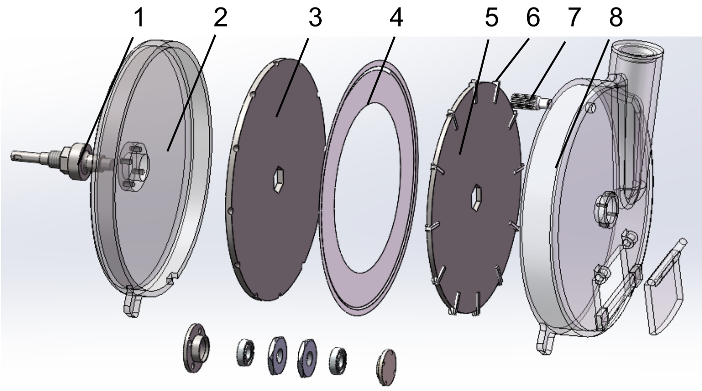


Fig. 1 - External structure of seed metering device
1 - Metering shaft; 2 - End cover; 3 - Seed dropping wheel; 4 - Separator plate; 5 - Seed picking wheel; 6 - Seed spoon; 7 - Seed cleaning brush; 8 - Housing

The operational cycle of the seed metering device includes six sequential stages: seed filling, unstable seed shedding, seed transfer, seed cleaning, seed transport, and seed sowing, as shown in Fig. 2.

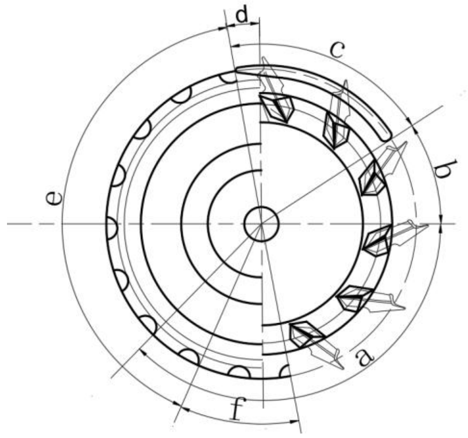


Fig. 2 - Schematic diagram of functional zones in seed metering device
a - Seed filling zone; b - Unstable seed shedding zone; c - Seed transfer zone; d - Seed cleaning zone; e - Seed guiding zone; f - Seed sowing zone

Vegetable seeds flow into the filling zone through the seed inlet channel. Under the drive of external power, the seed metering shaft rotates and activates the seed picking wheel and seed dropping wheel at the same time. Each seed picking spoon and separation plate form a seed-holding cavity. In the filling zone, a spoon scoops out multiple seeds from the seed mass, completely occupying their cavities before leaving the seed mass, and entering the sow zone after seed filling. In the shedding zone, unstably retained seeds detach from the spoons under dynamic forces and fall back into the seed mass of the filling zone. Spoons carrying stabilized seed quantities rotate to the transfer port of the separator plate. The seeds are fed into the corresponding seed receiving cells of the dropping wheel. Since each cell only accommodate one seed, the excess seeds are left in the spoon, completing the seed transfer process. At the end of the transfer zone, the seed cleaning brush removes residual seeds from the spoon. If the receiving cell is empty, the brushed seed supplements it. If the receiving cell is occupied, the brushed seeds will be returned to the seed mass in the filling zone.

The dropping wheel advances to the seed guiding zone. The seeds inside the receiving cells are fixed by the separator plate and housing guard, and can stably move to the discharge port at the bottom of the shell to complete seed guiding. At the discharge port, seeds are sprayed at a horizontal velocity opposite to the direction of machine movement. This balances the horizontal velocity during descent, achieving near-zero relative ground speed for precise placement onto the prepared seedbed to complete sowing.

Structural design of the seed picking wheel

The seed picking wheel is used as the seed collection and transfer component of the seed metering device. It mainly consists of seed picking spoons, spoon sockets, and the wheel disc, as shown in Fig. 3. The spoon sockets are fixed onto the wheel disc, and the seed picking spoons are plugged into the sockets. To improve the seed filling and transfer performance of the metering device and ensure broad adaptability to different vegetable seeds, the structural parameters of the seed picking spoons should be designed based on the physical properties of vegetable seeds.

This study uses the geometric parameters and orientation distribution probabilities of cabbage seeds to design the structural dimensions of the seed picking spoons. A multi-curvature combined-arc seed picking spoon has been developed, including three concave arc surfaces: the oblique-cut seed picking arc surface, the seed-holding transition arc surface, and the balanced seed-retention arc surface, as shown in Fig. 4. Oblique-cut seed picking arc surface: formed by the oblique intersection of an inclined cylinder and the cylindrical body at the spoon tip. Its inclination angle is determined based on the depth of the seed-holding cavity of the spoon. During seed mass filling and transport, this surface facilitates tangential seed separation and longitudinal seed guidance. Seed-holding transition arc surface: a spatial surface formed by sweeping a parabolic curve. It can effectively balance the seed weight, enhance stability during seed holding and transporting, and strengthen the seed cleaning effect of gravity. Balanced seed-retention arc surface: it supports seeds during transport, maintaining them in a state of dynamic equilibrium, as well as minimize seed damage during filling, transport and transfer. Consequently, the main structural parameters designed for the seed picking spoon include its length L, depth H, and wrap angle γ.

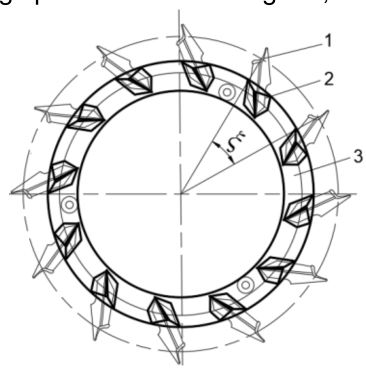


Fig. 3 - Structure diagram of the Seed Picking Wheel
1 - seed picking spoons; 2 - spoon sockets; 3 - wheel disc

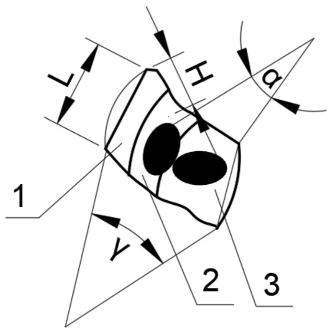


Fig. 4 - Structure diagram of seed picking spoons
1 - Oblique-cut seed picking arc surface; 2 - Seed-holding transition arc surface; 3 - Balanced seed-retention arc surface

The seed-holding space is a cavity formed by the three arc surfaces of the seed picking spoon and the planar surface of the seed separator plate. The volume of this cavity depends on the structural parameters of the seed picking spoon. Specifically, the length (L) and depth (H) are related to the triaxial dimensions of the cabbage seeds and their orientation when captured in the cavity, whereas the wrap angle is related to the angle of repose (β) of the seed mass. To ensure optimal seed filling and transfer performance of the seed picking spoon, the seed transfer angle (α) is designed.

The geometric parameter design follows the following principles:

$$\begin{cases} l < L < (1+cos\alpha)l \\ w < H < (1+sin\alpha)w \\ \beta > \gamma > atctan\left[1+\left(\frac{H}{L}\right)^2\right]^{-1} \end{cases} \tag{1}$$

The outermost seeds at the critical edge are the most unstable. Therefore, a kinetic analysis is conducted on a single outermost seed, as shown in Fig. 5. Based on D'Alembert's principle, the equilibrium force system equations are established as follows:

$$\begin{cases} mgsin(\varphi+\omega t)+F_s=F_{N_1}+F_e \\ mgcos(\varphi+\omega t)-F_{N_2}=ma_\tau \\ F_e=mR\omega^2 \\ F_s=\mu F_{N_2} \end{cases} \tag{2}$$

where, m is the seed mass, g; a_τ is the tangential acceleration of cabbage seeds, m/s^2; ω is the angular speed of spoon movement, rad/s; ($\varphi+\omega t$) is the rotation angle of seed collecting spoon (0, $\pi/2$), °; μ is the coefficient of friction between seeds; F_{N1} is the bearing force of seeds, N; F_{N2} is the push force of the spoon, N; F_s is the flying friction of the grains at the peripheral, N, and F_e is the centrifugal force of seeds, N.

Solving the second derivative of the radial decomposition force in Equation (2), then:

$$\frac{d^2F_{N_1}}{d\omega^2}=-Gt^2[sin(\varphi+\omega t)+\mu cos(\varphi+\omega t)]-2mR \tag{3}$$

Within the rotation angle interval (0, π/2) of the seed spoon, the second derivative value in Eq. (4) is consistently negative. This indicates that the radial force controlling seed retention in the spoon follows a downward-convex curve. Consequently, as the operational speed of the seed spoon increases, the radial force acting on the seed initially increases and subsequently decreases. Therefore, ensuring force balance at the inflection point is critical.

The seed picking wheel is designed with a rotational diameter of 200 mm and equipped with 12 seed picking spoons. To ensure effective single-seed feeding into the seed receiving cells of the seed dropping wheel, the seed picking spoons are designed to pick 1-2 seeds. Based on the principles of controlling seed orientation within the seed-holding cavity and the established spoon dimension design criteria, the structural parameters are determined: length L=3 mm, depth H=2 mm, wrap angle γ=(20~30)°, seed transfer angle α=(45~50)°.

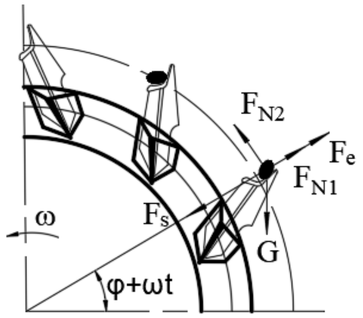


Fig. 5 - Diagram of the force applied to the moving seed

Structural design of the seed dropping wheel

The seed dropping wheel is used as the seed transport and discharge component of the seed metering device. Its function is to transport seeds fed from the receiving cells of the seed picking spoon to the discharge port area for release. The structural performance of the seed dropping wheel directly impacts seeding quality. An optimal seed transport and discharge trajectory facilitates zero-speed seeding. The seed receiving cells adopt a short isochronous curve contour, which can promote smooth seed feeding and discharging, ensure uniform seed spacing, and improve the accuracy of seed soft landing. This study investigates the motion trajectory of seeds during the delivery-to-landing process and designs a seed dropping wheel structure based on the brachistochrone principle. When a seed is discharged from the seed receiving cell at the discharge point, in a plane parallel to the central axis of the wheel (side view, O-XZ plane), the seed has a lateral horizontal velocity component with the initial speed v_x. The seed possesses a horizontal velocity component opposite to the forward direction of the wheel, with the initial speed v_y at the discharge port. In the vertical direction: due to the deviation between the seed position within the discharge cell and the centerline of the wheel, different centrifugal force components act on the seed during spraying. Therefore, the parabolic trajectory of the sprayed seeds requires spatial kinematic analysis. To analyze the motion of vegetable seeds during landing, a three-dimensional Cartesian coordinate system was established. The coordinate origin O is located at the initial seed release point, vertically aligned with the center of the seed-metering wheel. The cartesian coordinate system XOZ is established on the plane parallel to the central axis of the seed-metering wheel, and a Cartesian coordinate system YOZ is defined on the plane perpendicular to the central axis of the seed-metering wheel, as shown in Fig. 6.

The specific velocity equations are as follows:

$$\begin{cases} v = \varpi R \\ v_y = v\cos\sigma \\ v_z = v\sin\sigma \end{cases} \quad (4)$$

where, v is the linear speed of seeding wheel rotation, m/s; v_x is the component in the side horizontal direction of the sowing speed, m/s; v_y is the component in the front horizontal direction of the sowing speed, m/s; v_z is the component in vertical direction of the sowing speed, m/s; ω is the angular speed of seeding wheel rotation, rad/s; σ is the horizontal contained angle of seed throwing speed, °, and R is radius of the seed wheel, mm.

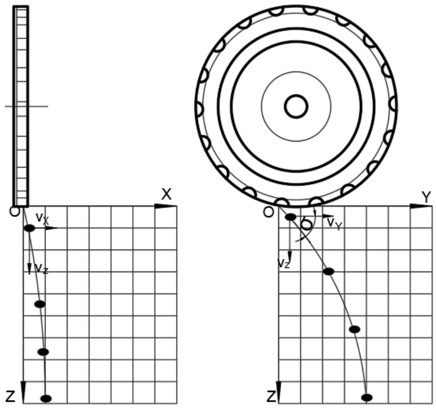


Fig. 6 - Kinematic analysis in dropping seed phase

Ignoring the influences of other factors in the sowing process, according to the momentum theorem, it could be obtained:

$$Ft_0 = mR\omega^2 t_0 = mv_x \quad (5)$$

Combining Eqs. (4) and (5), the trajectory equation of seed sowing could be obtained as follows:

$$\begin{cases} X = \varpi^2 \mathrm{R} t_0 t \\ Y = \varpi R t\cos\sigma \\ Z = \varpi R t\sin\sigma + \frac{1}{2} g t^2 \end{cases} \quad (6)$$

where, X is the horizontal displacement in the forward direction, mm; Y is the horizontal displacement in the lateral direction, mm; Z is the displacement in vertical direction, mm; t is the delivering time of the thrown seeds, s; t_0 is the time for the seeds to drop from the seeding wheel, s.

The kinematic analysis of the seed trajectory reveals that the release speed of the seeding device is opposite to the forward movement of the machine in the horizontal direction, thereby reducing horizontal velocity, lowering the release height, decreasing the vertical velocity at seed-soil contact in the vertical direction, and minimizing seed movement. According to the seeding quality standards and the principle of zero-speed seeding requirement, the horizontal displacement components are $X \approx 0$, $Y \approx 0$. The rotational linear velocity of the seed-metering wheel should be equal the travel speed of the seeder to ensure the shortest seed separation time. Using seed geometric parameters and orientation distribution probabilities as design inputs, and applying the principle of short-term curve truncation, the seed-cell structure of the metering wheel was designed. Through rotational scanning optimization of the truncated curve, the seed receiving cell is optimized to have a nearly spherical crown profile. The structural parameters include the cell opening diameter D, cell depth H, and parameters of the swept truncated curve. The design follows the principles: $D > H > l$.

The short-time truncation curve of the seed receiving cell surface is analyzed considering a mass point M rolling from the starting point O to the endpoint K, where K is not directly lower than O. When a circle with a radius r rolls along different paths, the trajectory traced by point M on its circumference is a short-time line that minimizes the travel time between O and K. The curve I in Fig. 7 shows this short-term line, let θ be the rotation angle of the circumference. The parametric equations of the brachistochrone trajectory are as follows *(Akhshik et al., 2015)*:

$$\begin{cases} x = r(\theta - \sin\theta) \\ z = r(1 - \cos\theta) \end{cases} \qquad \theta \in [0, \pi/2] \quad (7)$$

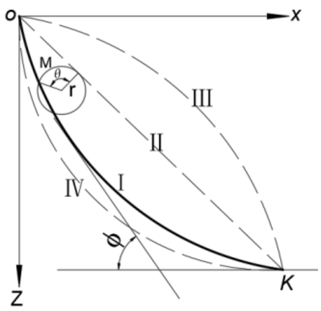


Fig. 7 - The principle of brachistochrone

Based on the kinematic model of seeds feeding into the cell during filling, when a seed rolls down at a height h, (where the maximum value equals the cell depth H), its lateral displacement is $\frac{1-\cos\theta}{\sin\theta}h$.

The work done by friction F_s along the brachistochrone path to the cell base is as follows:

$$\int_0^{\frac{1-\cos\theta}{\sin\theta}h} mg\cos\phi\tan\varphi dx = mgh\cos\phi\tan\varphi\frac{1-\cos\theta}{\sin\theta} \tag{8}$$

where, ϕ is the tangent inclination angle of the truncated curve at the sliding point, (º), and φ is the friction angle between seed and spoon, (º).

According to the law of conservation of energy, that is:

$$\frac{1}{2}m(v_z^2 - v_x^2) + mgh = mgh\,cos\,\phi\,tan\,\varphi\frac{1-cos\,\theta}{sin\,\theta} \tag{9}$$

where v_z is the initial descent speed of seeds, (m/s), and v_x is the seed termination horizontal speed, (m/s).

Combining and simplifying Eqs. (7) - (9), it can be obtained:

$$\frac{dz}{dx} = \frac{2gh\,\cos\phi\tan\varphi}{v_z^2 - v_x^2 + 2gh} \tag{10}$$

From this, the tangent inclination angle ϕ is as follows:

$$\phi = \arcsin\left[\sqrt{1 + \left(\frac{v_z^2 - v_x^2 + 2gh}{4gh\tan\varphi}\right)^2} - \frac{v_z^2 - v_x^2 + 2gh}{4gh\tan\varphi}\right] \tag{11}$$

The friction angle between the seed and the seed receiving cell is φ=20º-28º. Under ideal conditions with an initial seed velocity of v_z=0m/s and a final velocity at the cell base of v_x=0 m/s, a tangent inclination angle of ϕ =*23*º is obtained by substituting into Eq. (11).

Therefore, the design specifications of the seed dropping wheel are an outer contour diameter of 198 mm, an opening diameter D=2.0 mm of the seed receiving cell, a cell depth H=1.8 mm, and a tangent inclination angle of the cell surface ϕ =*23*º. The 12 seed receiving cells are evenly distributed.

Structural design of the separator plate

The separation plate located between the seed picking wheel and seed dropping wheel is an annular disc-shaped component made of 1.5 mm thick stamped steel sheet. The annular groove of the separator plate interfaces with the seed picking spoons to form the seed-picking cavity. During seeding, this plate remains stationary and does not rotate with the seed picking wheel or the seed dropping wheel. The plate has a sector shaped seed transfer port with an opening angle of θ, a tapered convergence angle δ at the port terminus, an opening width of b, as shown in Fig. 8. Adjacent seed picking spoons separated by an angle ξ fully feed seeds into the seed receiving cells of the dropping wheel in this port region.

This design prevents seed backflow and missed seeding events, according the following principles:

$$\begin{cases} 2\xi < \theta < 3\xi \\ \frac{3}{4}\xi \le \delta \le \xi \\ l < b < H \end{cases} \tag{12}$$

The separation plate is designed for safe installation in the shell, with a diameter of 204 mm. Its sector-shaped port has an opening angle of 70°, with a tapered convergence angle of 20° at the terminus and an opening width of 2 mm.

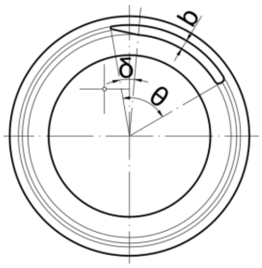


Fig. 8 - Structure diagram of the separator plate

Experimental Method

Experimental materials include the widely cultivated cabbage variety "Zhonggan 21"in Heilongjiang Province. The trials were conducted at the Seeding Performance Laboratory of Northeast Agricultural University. The experimental equipment includes a vegetable seeder with a separated type of picking and dropping and a JPS-12 computer vision seed metering performance test bench, as shown in Fig. 9.

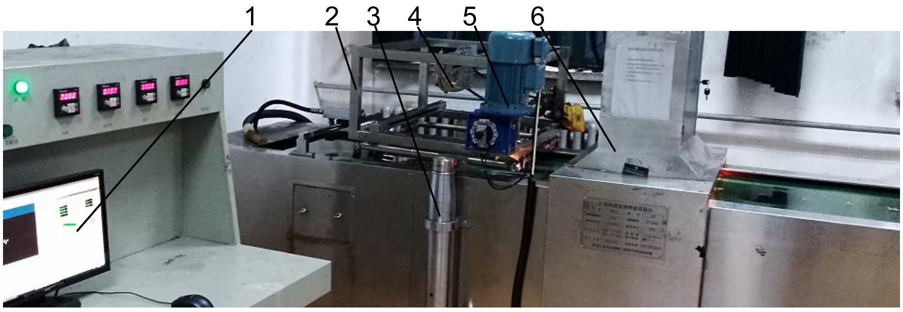


Fig. 9 - JPS-12 computer vision seed metering performance test bench
1 - Data analysis system; 2 - Mounting bracket; 3 - Frame lever; 4 - Seed metering device; 5 – Motor; 6 - Image acquisition system;

According to the structural principles and operational process of the seed metering device, the main factors influencing seeding quality and adaptable seeding range are the speed and tilt angle. Consequently, an optimization study focusing on these two factors was conducted. Referring to GB/T6973-2005 "Test methods for single seed drills " and JB/T1029-2001 "Specifications for single seed drills ", the seeding qualified index and coefficient of variation were selected as the test indicators to evaluate the performance of the seeder. A two-factor, five-level quadratic regression orthogonal rotational composite design was employed to determine the optimal operating parameters. The working speed v of the seeder is set in the range of 0.3 - 0.9 r/s, and the tilt angle ε was set in the range of -20~20° (Negative: tilted toward seed-picking wheel; Positive: tilted toward seed-dropping wheel).

RESULTS AND ANALYSIS

The working speed and tilt angle of the seed metering device were adjusted using the testing bench of the seed metering device. The seed distribution pattern observed during the tests is illustrated in Fig. 10. The experimental design scheme and measurement results are shown in Table 3. Design Expert 8.0.6 software was used for analysis, as shown in Table 4.

Fig. 10 - Distribution of seeds

Table 3
Experimental design and results

Number	Experimental factors			Performance indexes	
	working speed v / (r/s)	tilt angle ε / (°)		qualified index S / (%)	variable coefficient C / (%)
1	-1	-1		84.21	14.97
2	+1	-1		70.59	19.67
3	-1	+1		82.08	13.95
4	+1	+1		85.48	12.56

5	-1.414	0		89.35	10.32
6	+1.414	0		72.23	17.65
7	0	-1.414		76.81	16.69
8	0	+1.414		85.16	13.78
9	0	0		86.86	13.21
10	0	0		90.62	9.36
11	0	0		90.52	9.93
12	0	0		89.19	10.34
13	0	0		88.45	13.51
14	0	0		91.35	10.41
15	0	0		90.06	11.76
16	0	0		92.31	10.37

Table 4

Measured test data for variance analysis

Indexes	Sources	Sum of squares	df	Mean square	*F*	*P*
Qualified index	Model	633.28	5	126.66	27.87	< 0.0001
	v	148.19	1	148.19	32.61	0.0002
	ε	75.45	1	75.459	16.60	0.0022
	$v\,\varepsilon$	72.42	1	72.429	15.93	0.0026
	v^2	172.19	1	172.199	37.89	0.0001
	ε^2	165.03	1	165.03	36.31	0.0001
	Residual	45.44	10	4.54		
	Lack of Fit	24.76	3	8.25	2.79	0.1188
	Pure Error	20.68	7	2.95		
	Cor Total	678.73	15			
Variable coefficient	Model	111.86	5	22.37	8.66	0.0021
	v	23.38	1	23.38	9.05	0.0132
	ε	18.74	1	18.74	7.26	0.0226
	$v\,\varepsilon$	9.27	1	9.27	3.59	0.0874
	v^2	20.64	1	20.64	7.99	0.0180
	ε^2	39.83	1	39.83	15.42	0.0028
	Residual	25.83	10	2.58		
	Lack of Fit	9.16	3	3.05	1.28	0.3529
	Pure Error	16.68	7	2.38		
	Cor Total	137.70	15			

Note: ** means extremely significant (P < 0.01); * means significant (0.01 < P < 0.05), same as below.

As shown in Table 4, the working speed and tilt angle have an extremely significant impact on the sowing qualified index and coefficient of variation performance indicators. The regression equations for fitting the seeding qualified index and coefficient of variation are as follows:

$$S = 64.98+103.43v-0.63\varepsilon+1.42v\varepsilon-103.10v^2-0.02\varepsilon^2 \tag{13}$$

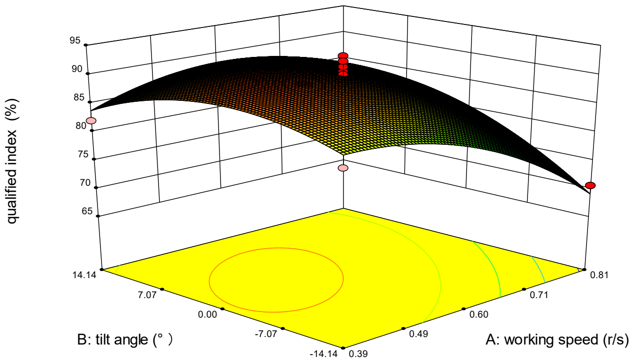
$$C = 19.13-34.77v+0.20\varepsilon-0.51v\varepsilon+35.69v^2+0.01\varepsilon^2 \tag{14}$$

To intuitively analyze the relationship between sowing indicators and experimental factors, Design Expert software is used to establish corresponding surfaces between the indicators and the two factors, as shown in Fig. 11.

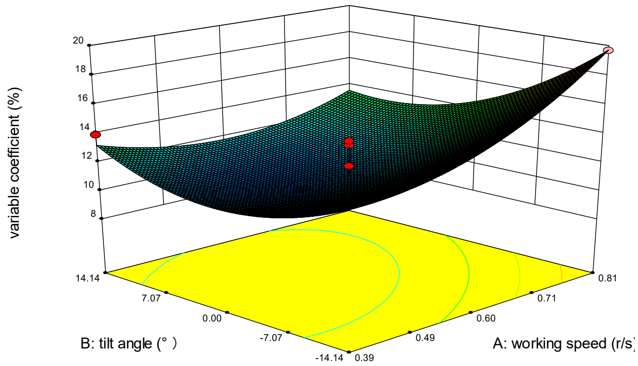
Based on the regression Eq. (13) and the corresponding response surface plot in Fig. 11(a), the following relationships are observed: as the speed increases, the qualified index of seed spacing initially increases then decreases. When the working speed is low, the change in the qualified index is gentle, and when it is high, the change increases significantly. The main reason is that the relatively fast rotational speed leads to a decrease in seed filling rate, making it easy to miss seeds. As the tilt angle changes from negative to positive, the qualified index first increases and then decreases. When the tilt angle is negative, the seed picking spoons tilts outward, and the effective volume of the seed picking cavity decreases, resulting in a decrease in filling rate. Seeds are not easily fed into the falling wheel cells and are not easily missed during sowing. When the tilt angle is positive, the seed picking spoons tilts inward, and the effective volume of the seed picking cavity relatively increases, resulting in an increase in filling rate. The seeds are easy to be fed into the dropping wheel cells for re-seeding. When the working speed is about 0.50 r/s and the tilt angle is about 4°, the qualified index is the highest.

Based on the regression Eq. (14) and the corresponding response surface plot in Fig. 11(b), the following relationships are observed: as the speed increases, the variable coefficient of seed spacing decreases first and then increases.

When the working speed is low, the variation in the coefficient of variation is relatively small and stable; however, as the speed increases, the variation grows significantly. This is mainly due to an increased likelihood of missed seeding events at higher speeds. As the tilt angle changes from negative to positive, the qualified index first decreases and then increases. When the tilt angle is negative, the variable coefficient of uniformity changes rapidly, and when it is positive, the change is gentle. When the working speed is about 0.5 r/s and the tilt angle is about 3°, the variable coefficient is the smallest.



(a) Effects of working speed and tilt angle on the qualified index



(b) Effects of working speed and tilt angle on the variable coefficient

Fig. 11 - Effects of working parameters on indexes

Based on of the experimental data, the optimal working parameters are determined, and each factor is subjected to optimization design. A parameterized mathematical model was established based on the agronomic requirements of vegetable sowing operations, taking into account the boundary conditions of various factors. Using a multi-objective optimization method, the regression equations for the qualified index of seed spacing and the coefficient of variation were analyzed to formulate the following nonlinear programming parametric model:

$$\begin{cases} \max S = f_1(r,\varepsilon) \\ \min C = f_2(r,\varepsilon) \\ s.t. \quad 0.30 \le v \le 0.90\ r \cdot s^{-1} \\ \quad -20 \le \varepsilon \le 20° \\ \quad 90\% \le S \le 100\% \\ \quad 0 \le C \le 12\% \end{cases} \tag{15}$$

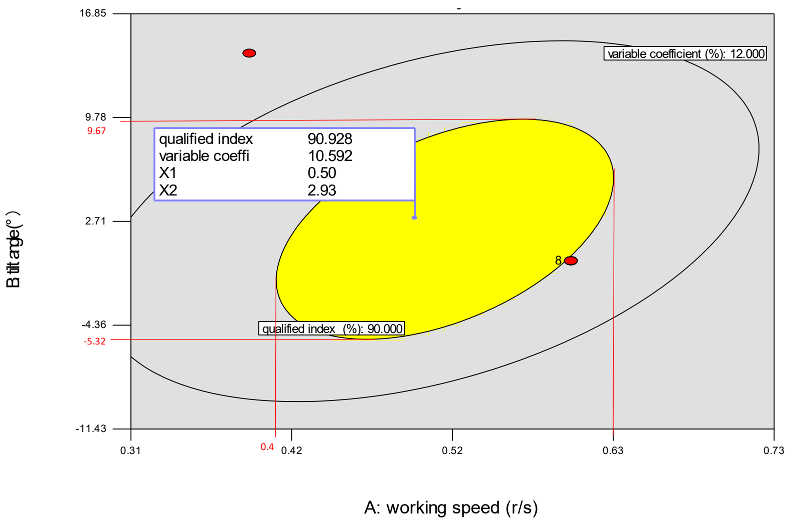


Fig. 12 - Diagram of parameters analysis

Based on optimization principles, Design-Expert software is used for parameter optimization The results demonstrate that the seed metering device can achieve optimal performance at an operational speed of 0.50 r/s and a tilt angle of 2.93°, with a qualified index of 90.93% and a variation coefficient of 10.59%. According to the optimization analysis, the optimal parameter combination interval is shown in Fig. 12. It is found that when the working speed is 0.40-0.63 r/s and the tilt angle is -5.32-9.67°, the qualified index of sowing distance is greater than 90%, and the variation coefficient is less than 12%.

CONCLUSIONS

Vegetable planter is an important component of mechanized vegetable cultivation, which directly affects the sowing quality and yield of vegetables. This study addresses the scarcity of mechanical seed metering devices suitable for small sized vegetable seeds. Through theoretical analysis, mechanical design, and prototype performance testing, the mechanism of a vegetable seed metering device was designed and analyzed. The main conclusions are as follows:

(1) Based on the physical properties of small-sized vegetable seeds (cabbage), a new precision seed metering device with separated seed picking and dropping functions was designed. Structural parameters of key components including the seed picking wheel, seed dropping wheel, and separator plate were analyzed and optimized;

(2) Bench tests identified the optimal operational parameter combination of working speed and tilt angle. Mathematical models correlating seeding performance metrics with experimental parameters were established. At an optimal operating condition of 0.5 r/s and a tilt angle of 2.93°, the device can achieve a qualified index of 90.93% and a variation coefficient of 10.59%. Optimization on the regression models confirmed that in the operational speed range of 0.40-0.63r/s and tilt angle range of -5.32-9.67°, the qualified index of seed spacing can exceed 90% and the Variation coefficient remained smaller than 12%, meeting seeding standards;

(3) The seed picking and dropping functions were performed by two separate components. The picking unit initially filled the seed-receiving cells of the dropping unit, which then transported the seeds to the discharge port for release. This two-stage precision metering process enabled continuous seed filling and discharge, significantly improving seeding accuracy. This innovative approach provided a new conceptual framework for the development of advanced vegetable seed metering technology.

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