DESIGN AND EXPERIMENTAL STUDY OF A BELT-TYPE PRECISION SEEDER WITH METERING CELLS FOR *FRITILLARIA* BASED ON EDEM SIMULATION
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基于 EDEM 的皮带窝眼式平贝母精量播种机设计与试验

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ABSTRACT
To address the challenges of low precision and limited mechanization in the precision seeding of field-grown Fritillaria, a belt-type precision seeder with metering cells was developed. Based on TRIZ theory, a conical–cylindrical cell with a hemispherical bottom was designed. The belt metering mechanism, driven by an electric motor, operated in coordination with a brush-type seed-retaining plate to achieve precision seeding of Fritillaria. The overall design of the machine was validated using EDEM simulation. Orthogonal experiments were conducted with forward speed, cell diameter, and seed drop height as test factors, and the seeding qualification rate as the evaluation index. The results showed that the optimal parameter combination was a forward speed of 0.88 km/h, a cell diameter of 24 mm, and a seed drop height of 75 mm. Under these conditions, the qualification rate reached 93.16%, meeting the requirements for precision seeding of Fritillaria.

摘要
针对大田平贝母精量播种精确度差、机械化程度低的技术难题，设计了一种平贝母皮带窝眼式精量播种机。基于 TRIZ 理论设计了一种锥柱形半球底式型孔，并采用电机驱动该窝眼机构与毛刷式护种板协同工作，完成平贝母的精量播种作业。采用 EDEM 离散元仿真验证了整机的合理性。以前进速度、型孔直径、投种高度为试验因素，以播种的合格率为评价指标进行正交试验，结果表明：最佳工作参数组合为前进速度为 0.88km/h、型孔直径为 24mm、投种高度为 75mm，此时合格率为 93.16%，符合平贝母精量播种要求。

INTRODUCTION
Fritillaria has the effects of clearing heat, moistening the lungs, and relieving cough and phlegm (*Aierken et al., 2021*), making it an important cultivation choice for traditional Chinese medicine growers in Heilongjiang Province (*Adamipour et al., 2025*). Due to the varying size and shape of fritillaria seeds, as well as strong specificity between varieties, the mechanization level in the cultivation process is low, becoming a bottleneck that restricts the development of the fritillaria cultivation industry in Heilongjiang Province. Therefore, addressing the lack of full mechanization in *Fritillaria* cultivation, the development of appropriate supporting machinery is of great practical significance for advancing mechanized production in Heilongjiang Province, promoting the transformation of the agricultural industry, and increasing farmers' income.

The seed metering device is a key component in the mechanized cultivation of *Fritillaria*. With increasing requirements for seeding quality, higher performance demands have been placed on seed metering devices. According to their working principles, seeders can be classified into mechanical and pneumatic types (*Obichayev, 2025; Deng et al., 2024; Akhalaya et al., 2021*). Mechanical seeders include hole-wheel, finger-clip, and external groove-wheel types (*Bangura et al., 2020; Baghooee et al., 2023; Emrah et al., 2021*), whereas pneumatic seeders mainly include air-blowing, air-suction, and air-pressure types (*Bustos-Gaytán et al., 2026; Kumar et al., 2017; Li et al., 2025*). Among these, mechanical hole-type seeders are the most widely used. However, their performance is limited by the dependence of hole size on seed size, which reduces versatility and complicates operation. In addition, problems such as seed damage and missed seeding still occur. Due to the irregular shape and fragile seed coat of *Fritillaria* seeds, hole-wheel seeders are not suitable for *Fritillaria* seeding (*Yin et al., 2024*).

Owing to the widespread issue of seed damage in mechanical seeders, increasing attention has been paid to pneumatic seeders by researchers worldwide. To reduce the influence of negative pressure on seeding performance, some researchers have analyzed the structure and operating principles of pneumatic seeders by establishing mathematical models relating experimental factors to performance indices, thereby improving seeding efficiency (*Kokuryu et al., 2011; Laryushin et al., 2021*). Others have mitigated the effects of vacuum fluctuations on seeding performance using pulse regulation and electromagnetic control technologies (*Liu et al., 2021; Padhiary et al., 2024*). In addition, vacuum-based peanut precision seeders have been developed using simulation tools such as MATLAB and ADAMS, reducing seed damage during operation (*Lbrahim et al., 2018; Alipour et al., 2022*). Furthermore, EDEM discrete element simulation combined with high-speed imaging has been applied to analyze seed motion during the seeding process (*Ghodki et al., 2019; Horabik et al., 2016; Jia et al., 2025*).

However, pneumatic seeders still present limitations: excessive air pressure can cause seed damage and breakage, while insufficient pressure leads to poor seed adsorption. Therefore, air-suction seeders are not suitable for *Fritillaria* seeding.

Although mechanical hole-type and pneumatic seed metering devices have been widely studied, their application to *Fritillaria* seeds remains problematic. Mechanical hole-type seeders often cause seed damage and missed seeding due to the mismatch between conventional cylindrical or conical hole geometries and the irregular, fragile morphology of *Fritillaria* seeds. Pneumatic seeders, while reducing mechanical contact, are highly sensitive to air pressure fluctuations: excessive pressure can damage seeds, whereas insufficient pressure results in inadequate seed adsorption. Furthermore, existing designs often lack dedicated seed protection mechanisms to prevent fragile seeds from being dislodged or damaged during the conveying process. Therefore, a clear research gap exists in the development of a seed metering device capable of simultaneously: (1) accommodating the irregular shape and fragility of *Fritillaria* seeds through optimized hole geometry; (2) ensuring reliable single-seed filling and conveying with minimal damage; and (3) operating robustly under field conditions without reliance on sensitive pneumatic systems.

To address this gap, this study aims to design and validate a novel belt-type precision seed metering device for *Fritillaria ussuriensis*. The primary objective is to achieve a high seeding qualification rate while minimizing seed damage. The methodology integrates theoretical design, discrete element simulation, and field experimentation. First, based on TRIZ theory, a conical–cylindrical cell with a hemispherical bottom was designed to improve seed filling and retention. Second, a motor-driven belt mechanism combined with a brush-type seed protection plate was employed to ensure gentle seed handling. The design was virtually prototyped, and the seeding process was simulated using EDEM software to optimize key parameters. Finally, a physical prototype was constructed, and its performance was evaluated through field experiments based on a Box–Behnken design. The novelty of this work lies in: (1) the application of TRIZ contradiction analysis to develop a specialized cell geometry for irregular *Fritillaria* seeds; and (2) the integrated use of EDEM simulation and response surface methodology to optimize and validate the performance of a belt-type precision seeder with metering cells for this crop.

MATERIALS AND METHODS

Structure and Working Principle of the Seeder

The overall structure of the *Fritillaria* belt-type precision seeder with metering cells is shown in Fig. 1.

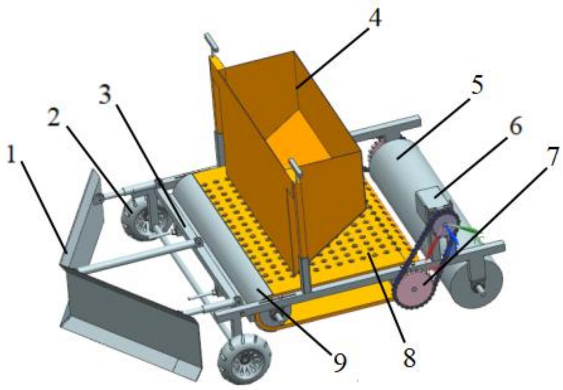


Fig. 1 - Structure of the belt-type precision seeder with metering cells for *Fritillaria*

1. Bulldozer blade; 2. Ground wheel; 3 Frame; 4. Seed box; 5. Press roller; 6. Variable-speed motor; 7. Transmission mechanism; 8. Seed metering belt; 9. Seed-retaining plate

It mainly consists of components such as a bulldozer blade, seed metering belt, seed box, seed-retaining plate, vibration motor, press roller, ground wheel, transmission mechanism, variable-speed motor, and frame. The metering cell is a critical component of the seed metering belt, and its geometry directly influences seed filling, protection, and seeding performance. During the design process, it is necessary to ensure smooth seed movement while allowing only a single seed to occupy each cell, thereby preventing multiple seeding. This requirement leads to a design contradiction. To resolve this issue, the local quality principle of TRIZ theory was applied by integrating the characteristics of cylindrical and hemispherical geometries, resulting in the design of a conical–cylindrical cell with a hemispherical bottom (Fig. 2). This geometry utilizes gravity during operation, allowing seeds to roll along the inclined surface into the cell. The proposed design ensures gentle seed handling, reduces missed and multiple seeding, and improves seed filling efficiency.

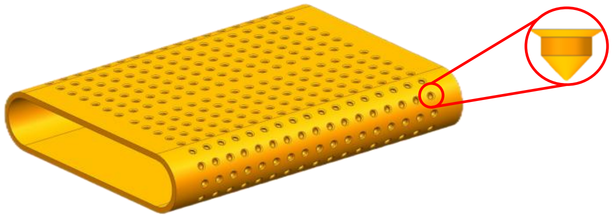


Fig. 2 - Geometry of the conical–cylindrical metering cell with a hemispherical bottom

The novelty of the proposed seeder lies primarily in the integration of a belt-type conveying system with a specifically designed metering cell geometry. Compared with conventional cylindrical or simple conical holes commonly used in hole-wheel seeders (*Baghooee et al., 2023; Bustos-Gaytán et al., 2026*), the conical–cylindrical cell with a hemispherical bottom (Fig. 2) is better suited to accommodate the irregular shape of *Fritillaria* seeds. The conical section guides the seed into the cell, while the hemispherical bottom supports the seed, reducing point contact and mechanical stress. This design directly addresses the technical contradiction identified using TRIZ theory, namely, the need for a sufficiently large opening to facilitate seed entry while ensuring a secure fit for single-seed retention. In addition, the use of a flexible brush-type seed-retaining plate, instead of rigid scrapers, further reduces seed damage during the seed-clearing and conveying processes. The proposed integrated design is expected to improve single-seed filling efficiency and seeding qualification rate while maintaining low levels of seed damage for fragile *Fritillaria* seeds.

Structural Design of the Seed Metering Belt

To ensure the stability of the seeding operation, the width of the seed metering belt was set equal to the bed width, i.e., 1200 mm. In addition, to reduce seed coat damage, simplify manufacturing, and lower costs, rubber sheets were selected as the primary material for the seed metering belt. Based on the calculated depth of the metering cells, the belt thickness was determined to be 20 mm. Considering that the machine is still at the experimental stage and in order to reduce costs, the belt length was set to 2000 mm.

According to the Agricultural Machinery Design Manual, the cell diameter can be determined using the following empirical relationship:

$$d = (1.3 \sim 1.9) l_{max} \tag{1}$$

where:

d is the cell diameter, [mm]

l_{max} is the maximum seed length of Fritillaria, [mm]

The maximum average length of *Fritillaria* seeds is 15.5 mm. Based on the above relationship, six candidate cell diameters were selected: 20 mm, 22 mm, 24 mm, 26 mm, 28 mm, and 30 mm. The holes in the seed metering belt were fabricated using a Z3032 radial drilling machine (Tiancheng Company) for cylindrical machining and chamfering (Fig. 3a), while an electric grinding tool (HILDA) was used to shape the hemispherical bottom (Fig. 3b).

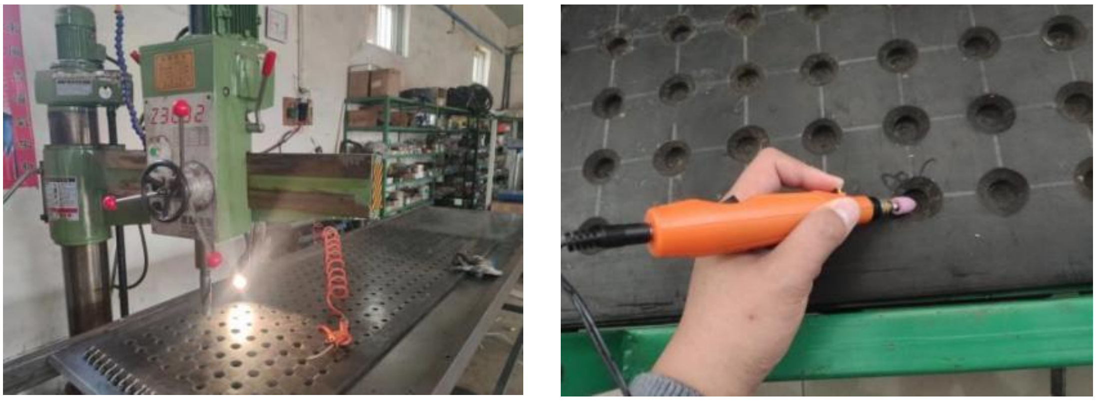


Fig. 3 - Drilling and chamfering of metering cells (a); forming of the hemispherical bottom (b)

Structural Design of the Seed Box

To ensure stable seed supply during operation, a seed reserve of at least 10% is typically maintained in the seed box.

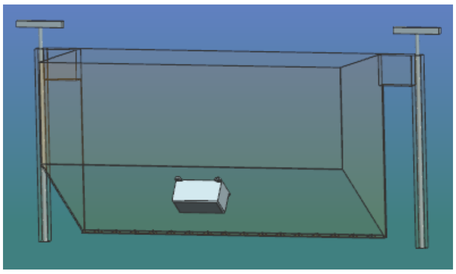


Fig. 4 - 3D model of the seed box

Accordingly, the seed box volume can be determined as:

$$V_L = \frac{1.1 L_1 B Q_{max}}{10000\gamma} \tag{2}$$

where:

V_L is the seed box volume, [L];
L_1 is the travel distance corresponding to a full seed box, [m];
B is the working width, [m];
Q_{max} is the maximum seeding rate per unit area, [kg/hm^2];
γ is the seed bulk density, [g/cm^3].

Based on a seeding rate of 6000 kg/hm² for small *Fritillaria*, the seed box volume was determined to be 120 L (Fig. 4). *Fritillaria* seeds are fragile and possess a seed coat that is highly susceptible to mechanical damage. Once the seed coat is damaged, germination and subsequent growth are significantly affected. Therefore, protecting seed integrity is a critical consideration in the design of the seed-cleaning mechanism. As shown in Fig. 5, flexible brushes are installed at the bottom of the seed box, functioning as both seed-cleaning and guiding elements. These brushes remove excess seeds from the metering cells, limit uncontrolled seed movement, and assist in directing seeds into the cells.

Fig. 5 - Brush structure of the seed box

Structural Design of the Press Roller

The press roller is used to embed seeds into the soil, improve seed–soil contact, reduce moisture loss, and promote seed germination and rooting. Common types of press rollers include cylindrical, concave–convex, conical composite, and rubber-ring types. Considering the fragile nature of *Fritillaria* seeds and mechanical design requirements, a cylindrical press roller was selected in this study.

The radius of the press roller is determined according to Equation (3):

$$R \geq \frac{\omega_r}{Qf} \tag{3}$$

R is the radius of the press roller, m;
ω_r is the friction torque, N·m;
Q is the gravitational force and additional load acting on the roller, N;
f is the soil–roller friction coefficient.

Based on compression tests conducted in the vertical direction, the minimum force required to embed *Fritillaria* seeds into the soil was determined to be 120 N, with a soil friction coefficient of 0.4. Accordingly, the radius of the press roller should not be less than 148.73 mm to ensure stable operation and proper seed–soil contact. Therefore, the roller diameter was set to 164 mm. In addition, the working length of the press roller was designed to match the bed width (1200 mm). To ensure that the applied pressure does not exceed the allowable limit of 120 N, the roller was designed with a hollow steel structure (wall thickness of 4 mm) and internal plastic filling to reduce weight while maintaining sufficient strength.

Structural Design of the Seed-Retaining Plate

The seed-retaining plate (Fig. 6) is designed to ensure that seeds remain within the metering cells during transport and are released only at the designated discharge position. The rear end of the seed-retaining plate is connected to an adjustable screw mechanism, allowing precise control of the clearance between the plate and the seed metering belt. According to the *Agricultural Machinery Design Manual*, the clearance between the seed-retaining plate and the edge of the seed metering belt should be maintained within 5–7 mm, with a wrap angle of 120°–160°. In addition, an offset angle of 10°–15° between the seed outlet and the vertical line of the metering cell is considered optimal. Given the relatively large size of *Fritillaria* seeds and the low seed drop height, the influence of airflow on seed trajectory is negligible. Therefore, no additional seed guide tube is required beneath the seed-retaining plate.

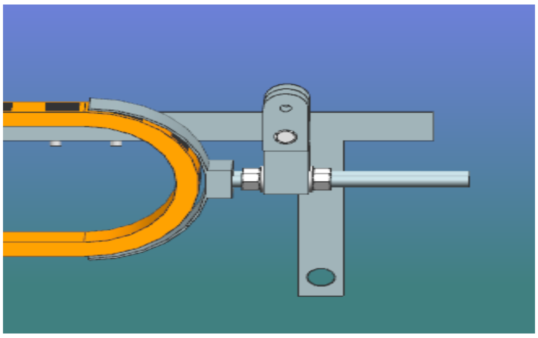


Fig. 6 - Structure of the seed-retaining plate

When the seed enters the release zone, it retains the tangential velocity imparted by the seed metering belt due to inertia. At the same time, the seed is subjected to gravitational force, resulting in a free-fall trajectory. The kinematic behavior of the seed during release is illustrated in Fig. 7. The ideal seeding condition is achieved when the horizontal (forward) velocity of the seed relative to the ground is zero at the moment of release. Under this condition, the seed falls vertically, minimizing displacement and improving seeding accuracy.

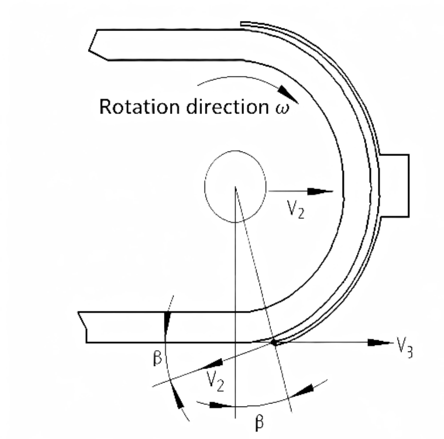


Fig. 7 - Kinematic analysis of seed motion during release

Based on the kinematic analysis, Equations (4) and (5) are obtained:

$$V_1 = V_2 \cos\beta \quad (4)$$

$$V_2 = \omega R \quad (5)$$

Combining the above equations yields:

$$\beta = \arccos(V_1/\omega R) \quad (6)$$

where: V_1 is the forward speed of the seeder, km/h;
V_2 is the linear speed of the seed metering belt, km/h;
ω is the angular velocity of the belt, r/min;
β is the optimal seed release angle, °;
R is the radius of the belt edge, mm.

From the above relationships, it can be seen that the seed release angle depends on the forward speed of the seeder, the rotational speed of the belt, and the radius of the belt.

Simulation Modeling

The seeds of *Fritillaria ussuriensis* are irregular, near-spherical particles. Discrete element method (DEM) simulation using EDEM software was employed to analyze the seed motion throughout the metering and discharge processes, enabling evaluation of key operational performance indicators and identification of potential design improvements.

Measurements of the three-dimensional geometry of *Fritillaria* seeds indicated an average length of 15.5 mm, a width of 14.4 mm, and a height of 12.8 mm. A three-dimensional seed model was constructed using CAD software and subsequently imported into EDEM. A multi-sphere (three-sphere) approximation method was used to represent the particle shape and define the contact model parameters. The seed density was determined experimentally and set to 1.042 g/cm³ in the simulation. Based on this value, EDEM automatically calculated the corresponding particle mass, volume, and related properties. The three-dimensional seed model used in the simulation is shown in Fig. 8.

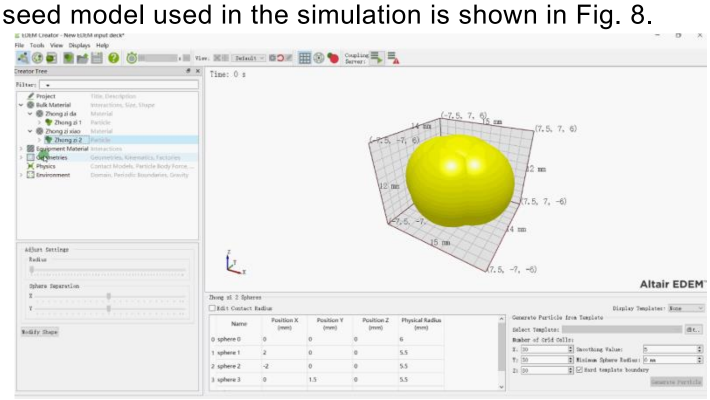


Fig. 8 - Three-dimensional DEM model of a *Fritillaria* seed

Simulation Material Parameters

The material parameters used in the DEM simulation are summarized in Table 1.

Table 1

Material properties and contact parameters used in DEM simulation

Material	Shear modulus （Pa）	Density （g/cm3）	Poisson's ratio	Contact pair	Rolling friction coefficient	Restitution coefficient	Static friction coefficient
Fritillaria.	1.26×108	1.042	0.32	Seed–seed	0.082	0.24	0.45
Seed metering belt	1.78×108	2.592	0.50	Seed and metering belt	0.093	0.56	0.44
Seed box	7×1010	7.945	0.30	Seed–seed box	0.010	0.61	0.32

The material properties of *Fritillaria* seeds, including Poisson’s ratio, shear modulus, and density, were determined experimentally using a texture analyzer and a density meter. The contact parameters, including the restitution coefficient and static and rolling friction coefficients between seed–seed and seed–material interactions (e.g., rubber belt and seed box), were obtained through laboratory tests such as the inclined plane method and direct shear tests, following the procedures described by *Bangura et al. (2020)* and *Li et al. (2022)*. These parameters were used as inputs in the DEM model to ensure simulation accuracy.

EDEM Simulation of Seeding Performance

The EDEM simulation experiments were conducted using a single-factor test method. Three factors were considered, with two factors held constant while the third was varied to evaluate its influence on seeding performance.

In the simulation, the seed metering device was set to a transparent state to allow clear observation of the seed filling, seed cleaning, and seed release processes, as shown in Fig. 9. Based on the theoretical analysis, seed filling performance was identified as a key evaluation index of the metering device. The distribution of *Fritillaria* seeds after operation (Fig. 10) was analyzed to assess seeding performance. The occurrence of multiple seeding (Fig. 11) and missed seeding (Fig. 12) was used to evaluate whether the seed filling performance met the required standards.

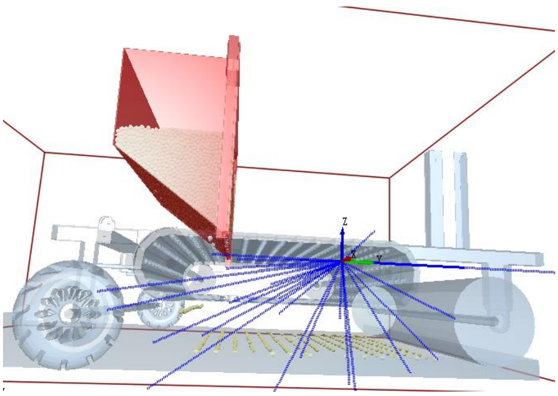


Fig. 9 - Simulation test

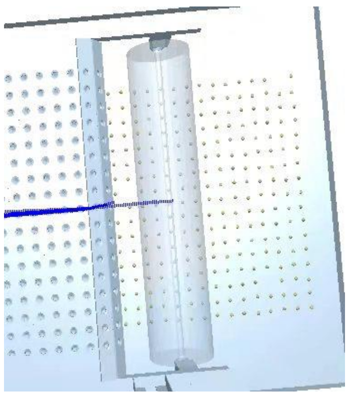


Fig. 10 - Test results

Fig. 11 - Multiple seeding

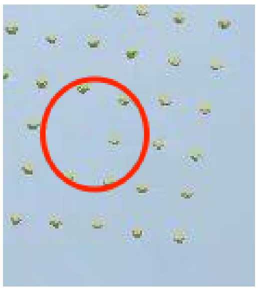


Fig. 12- Missed seeding

The seeding performance test and evaluation were conducted in accordance with the agricultural machinery industry standard JB/T 10293-2001, *Technical Conditions for Single-Seed Precision Planters*, and the national standard GB/T 6973-2005, *Test Methods for Single-Seed Precision Planters*.

A key performance indicator for precision seeders is the qualified spacing rate, denoted as A. The calculation is given by Equation (7):

$$A = \frac{n_0}{N} \times 100\% \tag{7}$$

where: n_0 is the number of qualified seed spacings;

N is the total number of measured spacings.

Simulation Results and Analysis

The test results are shown in Fig 13:

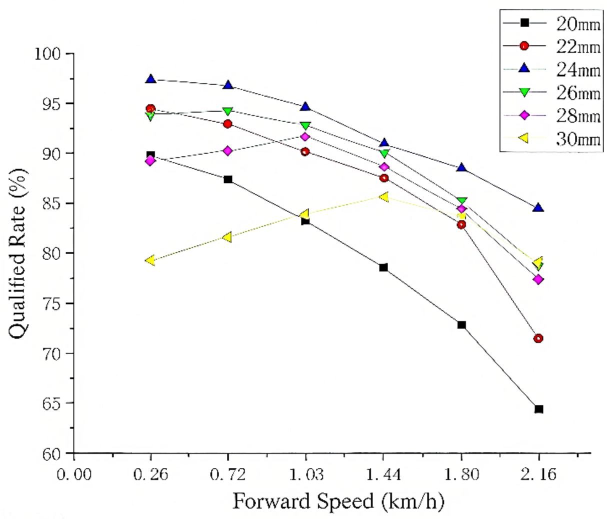


Fig. 13 - Effects of cell diameter and forward speed on the qualified seeding rate

To determine the optimal seeding performance, the effects of forward speed and cell diameter on the qualified seeding rate were analyzed (Fig. 13). The results show that the qualified rate decreases as the forward speed increases. At a forward speed of 2.16 km/h, the lowest qualified rate (64.35%) was observed for a cell diameter of 20 mm. In contrast, the highest qualified rate (97.35%) was achieved at a forward speed of 0.36 km/h with a cell diameter of 24 mm. Within the forward speed range of 0.36–1.44 km/h, the qualified seeding rate remained above 80%. Furthermore, within the range of 0.72–1.44 km/h, cell diameters of 22 mm, 24 mm, 26 mm, and 28 mm all achieved qualified rates exceeding 90%, with a maximum value of 96.72%.

To validate the EDEM simulation model, the optimal parameter ranges predicted by the simulation were compared with the results of field experiments. The simulation indicated that the qualified seeding rate remained above 90% within a forward speed range of 0.72–1.44 km/h and a cell diameter range of 22–26 mm (Fig. 13). Subsequent field experiments based on a Box–Behnken design identified the optimal parameter combination as a forward speed of 0.88 km/h and a cell diameter of 24 mm. The relative error between the center of the simulated optimal range (1.08 km/h, 24 mm) and the experimentally determined optimal speed was 18.5%, while the optimal cell diameter showed complete agreement. This consistency, particularly for the key factor of cell diameter, provides quantitative evidence supporting the validity of the EDEM model in predicting seeding performance trends.

Experimental Methods and Results

The selection of factor levels was based on preliminary single-factor experiments and agronomic considerations. The forward speed range (0.72–1.44 km/h) corresponds to the typical operating speed of small-scale precision seeders. The cell diameter range (22–26 mm) was determined based on EDEM simulation results and theoretical calculations using Equation (1). The seed drop height range (60–100 mm) was selected to represent typical distances from the seed release point to the soil surface in belt-type seeders.

To investigate the effects of forward speed, cell diameter, and seed drop height on the qualified seeding rate, an orthogonal experimental design was adopted. Field experiments were conducted using black soil with adequate moisture and good fertility. Experimental plots were prepared as flat beds suitable for *Fritillaria* cultivation, with dimensions of 10 m × 1.2 m. The experimental setup is shown in Fig. 14. During the tests, seeding performance data were collected under stable operating conditions, and seed spacing measurements were recorded as illustrated in Fig. 15. The experimental results were subsequently analyzed to determine the optimal parameter combination.

Fig.14 - Field test

Fig.15 - Distribution of seeds after field seeding

A Box–Behnken experimental design was established using Design-Expert software to investigate the effects of forward speed, cell diameter, and seed drop height on the qualified seeding rate. These three variables were selected as independent factors, while the qualified seeding rate was used as the response variable. The factor ranges were determined based on preliminary experiments and simulation results: forward speed (0.72–1.44 km/h), cell diameter (22–26 mm), and seed drop height (60–100 mm). A three-level coding scheme was adopted for each factor, as shown in Table 2.

Table 2

Factor levels and coding for the Box–Behnken design

Level	Factor coding		
	Forward speed (km/h)	Cell Diameter (mm)	Seed drop height (mm)
-1	0.72	22	60
0	1.08	24	80
1	1.44	26	100

To reduce the number of experimental runs while considering the interactions among factors, a Box–Behnken design (BBD) was adopted. The experiment consisted of 17 runs. Each run was conducted with three replications, and the average values were used for analysis. During each test, the seeder operated over a 10 m distance under stable conditions. A total of 207 consecutive seed spacings were recorded and evaluated according to Equation (7) to determine the qualified seeding rate. The experimental results are presented in Table 3.

Table 3

Experimental design and results based on the Box–Behnken design

Run	Experimental factors			Performance indicators
	Forward speed (km/h)	Cell Diameter (mm)	Seed drop height (mm)	Qualified seeding rate (%)
1	0	0	0	91.73 ± 1.05
2	1	0	1	83.53 ± 1.89
3	0	0	0	91.63 ± 0.92
4	1	1	0	81.32 ± 1.33
5	-1	-1	0	85.79 ± 1.21
6	-1	1	0	79.36 ± 0.98

Run	Experimental factors			Performance indicators
	Forward speed (km/h)	Cell Diameter (mm)	Seed drop height (mm)	Qualified seeding rate (%)
7	1	0	-1	85.03 ± 1.47
8	-1	0	-1	90.42 ± 0.36
9	0	0	0	92.92 ± 1.68
10	-1	0	1	84.51 ± 0.35
11	0	1	1	74.61 ± 0.78
12	1	-1	0	81.08 ± 1.42
13	0	1	-1	81.39 ± 0.86
14	0	0	0	91.15 ± 1.34
15	0	-1	1	79.84 ± 0.93
16	0	-1	-1	81.95 ± 0.82
17	0	0	0	93.37 ± 1.65

Note: Values are presented as mean ± standard deviation (n=3). For each experimental run, the seeder operated over a distance of 10 m, and 207 consecutive seed spacings were measured to calculate the qualified seeding rate.

The experimental results were analyzed using Design-Expert software to establish a quadratic regression model describing the relationship between the qualified seeding rate and the three factors: forward speed, cell diameter, and seed drop height. Analysis of variance (ANOVA) was performed to evaluate the significance of the model, individual factors, and their interactions. The results are presented in Table 4.

Table 4

Analysis of variance (ANOVA) for the qualified seeding rate

Test Indicators	Variance Source	Sum of squares	Degrees of freedom	Mean square	F-value	p-value
Qualified seeding rate	Model	503.17	9	55.91	71.68	<0.0001
	X_1	10.4	1	10.4	13.33	0.0082
	X_2	17.94	1	17.94	23	0.002
	X_3	33.21	1	33.21	42.58	0.0003
	X_1X_2	11.12	1	11.12	14.26	0.0069
	X_1X_3	4.86	1	4.86	6.23	0.0412
	X_2X_3	5.45	1	5.45	6.99	0.0332
	X_1^2	15.58	1	15.58	19.98	0.0029
	X_2^2	293.48	1	293.48	376.29	<0.0001
	X_3^2	80.18	1	80.18	102.8	<0.0001
	Residual	5.46	7	0.78		
	Lack of fit	1.93	3	0.64	0.73	0.5855
	Pure error	3.53	4	0.88		
	Total	508.63	16			

Regression model

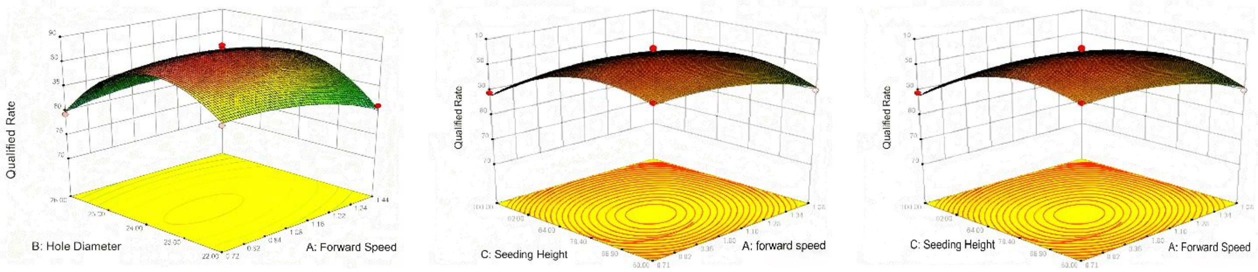
According to Table 4, the regression model for the qualified spacing rate is highly significant ($p < 0.0001$), indicating that the model is reliable and can accurately describe the relationship between the factors and the response. Using Design-Expert 10.0 software, a quadratic regression model was fitted based on the coded variables, as expressed in Equation (8):

$$Y_1=92.16-1.14X_1-1.50X_2-2.04X_3+1.67X_1X_2+1.10X_1X_3-1.17X_2X_3-1.92X_1^2-8.35X_2^2-4.36X_3^2 \quad (8)$$

As shown in Fig. 16a, with the seed drop height fixed at $H = 80$ mm, the qualified spacing rate exhibits a convex relationship with cell diameter. Increasing the cell diameter improves seed filling for irregular *Fritillaria* seeds; however, excessive diameters (> 24.5mm) lead to multiple seeding, especially at higher forward speeds where seed settling time is limited. Conversely, smaller diameters (< 22.5mm) increase the probability of missed seeding due to insufficient accommodation of seeds. The significant interaction between forward speed and cell diameter (X_1X_2) indicates that at lower speeds (0.72–0.88 km/h), the system maintains high tolerance to variations in cell diameter, with qualified spacing rates exceeding 90%. However, when the forward speed exceeds 1.2 km/h, the optimal diameter range becomes narrower, requiring more precise parameter control.

As shown in Fig. 16b, with the cell diameter fixed at 24 mm, the qualified spacing rate initially increases and then decreases with increasing forward speed. Moderate speeds improve seed trajectory alignment, while excessive speeds (> 1.3 km/h) cause seed rebound and instability, reducing seeding accuracy. The relatively weak interaction between forward speed and seed drop height suggests that the height can be adjusted within a moderate range (70–85 mm) without significantly affecting performance, provided that the forward speed remains below 1.2 km/h.

As shown in Fig. 16c, with the forward speed fixed at V=1.08 km/h, the interaction between cell diameter and seed drop height significantly affects performance. A seed drop height of approximately 75 mm provides optimal conditions, balancing gravitational filling and minimizing seed impact. Deviations from this value, particularly when combined with non-optimal cell diameters, result in a noticeable decrease in the qualified spacing rate, indicating the sensitivity of *Fritillaria* seeds to drop dynamics.



(a) (b) (c)

Fig.16 - Response surface plots showing the interactive effects of (a) forward speed and cell diameter, (b) forward speed and seed drop height, and (c) cell diameter and seed drop height on the qualified spacing rate.

Optimal Parameter Combination

To determine the optimal operating parameters, the numerical optimization module of Design-Expert 10.0 software was used. The seed drop height was initially fixed at 80 mm, with the optimization criteria set as follows: a qualified spacing rate greater than 90%, and both multiple seeding rate and missed seeding rate less than 5%. The optimization results are shown in Fig. 17.

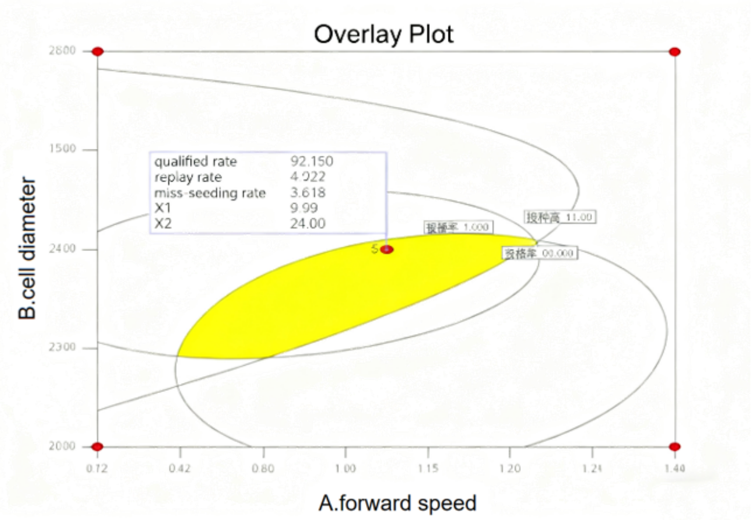


Fig. 17 - Parameter analysis diagram

As shown in Fig. 17, the optimal parameter region (highlighted in yellow) corresponds to a forward speed range of 0.82–1.30 km/h and a cell diameter range of 23–24.4 mm when the seed drop height is fixed at 80 mm.

Based on the regression model, the optimization problem can be expressed as:

$$\overline{X} = \{X_1, X_2, X_3\}$$
$$max/\min: y = f(x_1, x_2, x_3) \tag{9}$$

subject to:

$$0.72\text{km/h} \le x_1 \le 1.44\text{km/h}$$
$$22\text{mm} \le x_2 \le 26\text{mm}$$
$$60\text{mm} \le x_3 \le 100\text{mm}$$

The optimal parameter combination was determined as a forward speed of 0.88 km/h, a cell diameter of 24 mm, and a seed drop height of 75 mm. Under these conditions, the qualified spacing rate reached 93.16%. The achieved qualified spacing rate of 93.16% demonstrates the effectiveness of the proposed conical–cylindrical cell design for handling irregular *Fritillaria* seeds. Compared with conventional mechanical seeders, which often experience seed jamming and multiple filling due to irregular seed morphology (*Baghooee et al., 2023; Emrah et al., 2021*), the proposed design significantly reduces these issues. Although the obtained performance is slightly lower than the highest precision reported for pneumatic seeders operating with uniform seeds (*Li et al., 2025*), it represents a practical engineering trade-off. The proposed mechanical system prioritizes seed coat integrity, structural simplicity, and cost-effectiveness, while avoiding the complexity and potential seed damage associated with pneumatic systems.

CONCLUSIONS

(1) To address the challenges of mechanized seeding of irregular and fragile *Fritillaria* seeds, a belt-type precision seeder with metering cells was developed. Based on TRIZ contradiction analysis, a conical–cylindrical cell with a hemispherical bottom was designed, which effectively balances rapid seed entry and stable single-seed retention.

(2) The integration of EDEM-based discrete element simulation and field experiments enabled a comprehensive evaluation of seeding performance. The simulation accurately predicted the optimal cell diameter (24 mm); however, a relative error of 18.5% in the optimal forward speed indicates that further refinement of the simulation model is required, particularly in representing seed–soil–belt interactions.

(3) Field test results showed that the qualified spacing rate reached 93.16%, demonstrating that the proposed mechanical seeding approach is a viable alternative to pneumatic systems. The design emphasizes seed coat protection, structural simplicity, and cost-effectiveness, making it well suited for small-scale *Fritillaria* cultivation systems.

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