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Abstract

To solve the problems of high seed replaying rate and seed missing rate in the existing potato seed-metering device, a triangle chain claw potato seed-metering device was designed. Based on the discrete element method (DEM), the influence of seed picking claw and seed cleaning plate on the seed-metering process was analyzed. An orthogonal experiment was carried out with lateral spacing, vertical spacing, and terminal radian of the seed picking claw as experiment factors and the qualification rate as experiment indicator. The influence of relevant factors on seed picking performance was analyzed, and the optimal solution of seed picking claws was obtained. The target rate was 89.93% when the lateral spacing of the claw was 29.92 mm, the vertical spacing was 15 mm, and the terminal radian was 29.25°. Moreover, a single factor experiment was carried out with the angle of the seed cleaning plate as the experiment factor and the qualification rate and seed missing rate as the experiment indicators. The results showed that when the angle of the seed cleaning plate was 7.53°, the qualification rate was 90.1%, and the seed missing rate was 3.7%. In addition, an orthogonal experiment was carried out with seed picking speed, different types of seed picking claw, and the angle of seed cleaning plate as experiment factors, and the seed replaying rate and the seed missing rate as experiment indicators. Finally, the results of the simulation experiment were experimented on the bench, and the seed replaying rate was 2.7%, and the missing seeding rate was 1.9%.

Key words: structural parameters; seed filling performance; seed clearing; orthogonal experiment

Introduction

Potatoes are the fourth most important food crop in terms of area, yield, and value, after rice, wheat, and maize (Elsadig *et al*., 2010). China currently accounts for the world's largest area under potato cultivation and total production, but mechanized production levels still lag far behind other developed countries such as America and Germany (Lv *et al*., 2015). An important part of this is the mechanized sowing of seeds, and the core unit of the seed planter is the seed metering device. The potato seed metering device is divided into the pneumatic and mechanical types (Chen *et al*., 2021). The former has low requirements on the geometric size of potato seed, good versatility, no damage to seeds, and high efficiency, but it has a complex structure and high price (Boyda, 2017). The latter mainly include spoon belt (chain) type, spoon disc type, needle type and pickup finger type (Shi *et al*., 2018). Among them, the spoon chain device is more widely adopted due to its high reliability and versatility. However, it has a relatively high rate of missed seeding (Buitenwerf *et al*., 2016). The seeding process involves selecting, cleaning, transporting and dosing seeds. Improving the seed picking performance of the seed scoop is critical to improving the seeder's operational performance. The motion behavior of the potato seed particles during the seed metering process using a self-designed across-bridge metering device by discrete element method (DEM) was investigated, and it was found that improving the seed filling performance of the seed scoop was effective in reducing the rate of missed seeds (Shi *et al*., 2022). However, it is designed to deliver spherical potato seed and the distribution structure needs to be redesigned for irregular seeds.

In recent years, DEM has been used to study the movement of seeds in a device and to optimize the structure of devices (Peng *et al*., 2016). DEM is an effective tool for the investigation of microscopic properties of particles when transient forces and energy dissipation cannot be studied by conventional experimental methods (Moreno-Atanasio *et al*., 2012). DEM was used to evaluate the metering systems (Barr *et al*., 2019), optimize the structure and movement parameters of the metering unit with upper and lower seed boxes (Niu *et al*., 2016), and simulate the effect of particle shape on movement and mixing in a rotary batch seed coater (Pasha *et al*., 2016). Therefore, DEM technique is a relatively well-established method for studying seed movement and optimizing seed discharge structures and can be used to investigate the seed metering process in potato seeder.

Chunky potatoes are widely used as seed for seed metering, but their irregular shape and poor mobility result in poor seed filling capacity. In addition, the currently available spoon chain seed meter suffers from high reseeding and missed seed rates. In response to this problem, a triangular chain claw type potato seed metering device is designed, which adopts the "take more and leave one" method of seed picking. In addition, the influence of the seed picking claw and seed cleaning plate on the seed metering process was analyzed using DEM. Furthermore, the influence of relevant factors on the seed picking performance was analyzed and the structure of the seed picking claw was optimized.

Materials and Methods

Potato model

The performance of the potato seed-metering device was analyzed and optimized by the discrete element method. The size is an important factor affecting potato seed filling. To study the seed filling capacity, the potato model was created as a quarter ellipsoid, and, the long axis is 100 mm and the short axis is 80 mm, as shown in Figure 1a, potatoes was created with multi-sphere combination filling, as shown in Figure 1b. In terms of seed potato, the density is 1048 kg/m^3, Poisson's ratio is 0.57, and shear modulus is 1.34×10^6 Pa(Shi *et al.*, 2022). The mass, volume, and moment of inertia are calculated automatically by EDEM software.

Seed-metering device model

The potato seed-metering device is mainly composed of an active drive assembly (the electric motor and the reducer drive the driving sprocket through the chain drive), double-row seeding assembly (double-row triangle chain and claw-type seed spoon), seed filling box, frame, driving shaft, driven shaft, and seed cleaning device. Among them, the seed picking claws are symmetrically distributed on the seed picking chain. The seed-picking claws are arranged on the steel plate by three arcs of 6mm steel bars, and the edges are folded into an arc shape. In this way, the damage to the seed potatoes from falling off the seed picking claws during the seed picking process is reduced. The bottom of the seed picking claws is equipped with a seed picking spoon with a diameter of 20 mm. The seeding chain and the seed box are welded by four support plates to prevent many seed potatoes from bending the chain and the phenomenon of entrainment during the seed picking process. The seed cleaning device is composed of four slanting baffles. In the process of seed potato lifting, the bulk density space is constantly reduced, and the excess seed potato is squeezed out and dropped into the seed box. The potato seed-metering device has a simple structure and is easy to operate, which is shown in Figure 2a. The working process of the potato seed-metering can be divided into four stages: seed filling stage, seed clearing stage, horizontal conveying stage, and seed guiding stage. During the operation, potatoes reach the bottom to fill seeds under the action of gravity, and a flowing potato group is formed under the drive of the seed spoon. The seeds were collected under the combined action of gravity, friction between seeds, and claws. The power is driven by the motor through the chain drive to mobilize the driving shaft, which drives the seed-metering chain and the seed picking claw to move smoothly from bottom to top. The claws were forced to collect multiple potato seeds and then enter the seed cleaning area. The seed clearing device is composed of an angled steel plate. During the rising stage of seed potatoes, the volumetric space is gradually reduced, and the excess seed potatoes are squeezed out of the seed spoon. The seed potatoes enter the horizontal conveying area. If there are still many seed potatoes in the seed spoon, the seed potatoes vibrate under the vibration of the chain and fall back to the seed box to achieve the purpose of secondary seed cleaning. If the seed potato is not captured in the seed spoon, artificial reseeding can be carried out to ensure single seed picking and complete seed cleaning. Then, the seed potatoes fall on the back of the previous seed spoon under the action of gravity, and the two adjacent seed picking claws and the seed stop plate form a closed space to guide the seeds smoothly. When the seed potato reaches the seeding point, it loses its support, and the seeding process is completed under the action of centrifugal force. The established simulation model of seeding is shown in Figure 2c, and the size of seed box is seen in Figure

2d. To reduce the simulation time and simplify the seed picking model, four parts of single-row seed picking, seed box, seed cleaning plate, and seed picking claw were set up. The CAD model of seed potato was cut by 3D modeling and experimenting software and imported into EDEM.

Simulation parameters

Hertz-Mindlin (no-slip) contact model are adopted for contact model between the seed potatoes and the seed picking device (Coetzee, 2017). The seed metering device includes the seed clearing plate, the seed box, and the seed picking claw, and they are all steel material. Simulation parameters are seen in Table 1.

Results and Discussion

The influence of the size of the seed picking claw on the number of seed picking

Through the pre-stimulation experiment, it is found that when the seed picking speed is 0.5 m/s, the seed picking effect is good. To achieve the purpose of "picking more," the influence of the structural parameters of the claw on the number of seeding was analyzed. The spacing of the seed picking claw (*a*), the length (*b*) of the middle claw installed lower than that of the two side claws, and the terminal radian (*r*) of the claw was set as variables, respectively. The structure of the seed picking claw is shown in Figure 3. The results of the seed picking claw with different structural parameters are displayed in Figure 4.

As displayed in Figure 4a, two potato seeds were captured with the seed picking claw and arranged in vertical rows. If the claws capture more than 2 seeds, it will bring a burden to the clearing process, and due to the irregular arrangement, empty seeds are prone to occur during the clearing process. As displayed in Figure 4 b,d,e,f, four potato seeds were captured with the seed picking claw and arranged in vertical rows. Due to many seeds, insufficient seed clearing is likely to occur, resulting in there being still many seed potatoes in the seed spoon, which cannot meet the purpose of "reserving one". The situation in Figure 4c is similar to that in Figure 4a. However, due to the small terminal radian of the claw, the seed potatoes are easily thrown out of the seed-taking claw when overrunning the driving wheel, resulting in an empty spoon. In order to obtain better structural parameters of seed picking claw, seed picking experiments were carried out under different structural parameters of seed picking claw. The experiment factors and levels are shown in Table 2.

According to the design concept of "take more and leave one", when the seed picking claw captures the seed potato, it needs to meet the requirements of picking 2 to 3 seeds at a time, and the qualification rate of seed picking is calculated by Eq. (1). The results of the seed picking simulation experiment are shown in Table 3.

$$Y_1 = y/Y \times 100\% \qquad \text{(Eq. 1)}$$

where Y_1 is the qualification rate of seed picking, %; y is the number of times picking 2 to 3 seed potatoes in the experiment; and Y is the total number of seed picking.

In terms of the experiment results in Table 3, Design-Expert was used to perform multiple-regression fitting on the data, and the regression equation of qualification rate Y_1 was as follows. Variance analysis was conducted on the experiment results, and the results are shown in Table 4.

$$Y_1 = -607.47 + 4.14X_1 + 18.36X_2 + 32.63X_3 - 0.126X_XX_2 - 0.285X_1X_3 - 0.203X_2X_3 + 0.13X_1^2 - 0.28X_2^2 - 0.377X_3^2 \qquad \textit{(Eq. 2)}$$

According to the results in Table 4, the qualification rate Y_1 of seed picking in the response surface model p is 0.0196, indicating that the model is significant. The non-fitting term is not significant, indicating that the model is reliable, and the structural parameters can be optimized by this model. The influence of each factor on the qualification rate of seed picking is shown in Figure 5.

As revealed in Figure 5a, when the terminal radian of the seed picking claw is 32°, the qualification rate of seed picking increases with the increase of vertical spacing and lateral spacing, and the influence of lateral spacing on the indicator is slightly less than that of vertical spacing. As can be seen from Figure 5a, when the lateral spacing is 30 mm, and the terminal radian is constant, the qualification rate of seed picking increases first and then decreases with the increase of the vertical spacing of seed picking claws. When the vertical spacing of the picking claw is constant, the qualification rate of the picking claw increases first and then decreases with the increase of the terminal radian, and the influence of the terminal radian is slightly less than the longitudinal length of the picking claw. As revealed in Figure 5c, when the vertical spacing is 15 mm, and the terminal radian is constant, the qualification rate of seed picking increases with the increase of seed picking claw. When the lateral spacing of the claw is constant, the qualification rate increases first and then decreases with the increase of the terminal radian. According to the above analysis, the optimal combination was obtained by the optimization equation: when the lateral spacing of the seed picking claw was 29.92 mm, the vertical spacing was 15.00 mm, and the terminal radian was 29.25°, the qualification rate of seed picking was 89.93%.

Influence of seed picking speed on seed filling performance

To study the influence of seed picking speed on seed filling performance, seed picking speed was set as 0.4 m/s, 0.5 m/s, and 0.6 m/s, respectively. The simulation process is shown in Figures 6, 7, and 8.

As can be seen from Figure 6, after the last seed picking, there will be an empty space below it. If the claw cannot be backfilled, the empty seed will be caused. There was little difference in the speed between the seed potato on the seed picking claw and the seed potato moving at a low speed nearby. In the process of the claw entering the population, moving to the middle position, and leaving the population, the speed of the seed potato on the seed picking claw is not much different from that of the population, so it is easy to pick seeds. It can be seen from Figure 7 that before seed picking claws entered the population, most seed potatoes moved mainly in green low-speed motion. When the previous seed picking claw takes the seeds, the speed of the seed potatoes around the claw increases so that the lower space can be well backfilled, and the probability that the lower seed picking claw cannot get the seed potatoes is reduced. There is an obvious difference between the speed of seed potatoes around the seed picking claw and the speed of the seed potatoes in the population. The seed potatoes are not easy to be compacted and are easy to clear. As can be seen from the Figure 8, 2~3 seed potatoes can be taken from the seed picking claw each time, which is in line with the design expectation of the claw. It can be seen from Figure 8 that the number of potato seeds marked in red in the population increases, and the population disturbance increases. The number of high-speed potatoes marked in red around the seed picking claws increased, and the backfilling after the last seed picking was not significant, resulting in insufficient seed filling of the next-level seed potatoes. Moreover, the state of the potato seeds is unstable., which easily leads to the occurrence of an empty seed phenomenon.

Influence of the angle of seed clearing plate on seed cleaning

It can be seen from the above analysis that when the seed picking speed is 0.5m/s, the seed picking effect is good. If the angle of the seed clearing plate is too large, the length of the picking claw will be lengthened, and the whole experiment bed will be too large. If the angle of the seed clearing plate is too small, the seed cleaning will not be sufficient, and the expected cleaning effect cannot be achieved. In order to analyze the influence of the seed cleaning plate on the seed cleaning effect, the angle of the seed clearing plate was set at 6°, 9°, and 11°, respectively. Then, seed cleaning simulation analysis was carried out, as displayed in Figure 9.

As displayed in Figure 9, when the angle of the seed clearing plate is 6°, there are still 1-2 seed potatoes in the claw when the claw reaches the top part, indicating that the effect of seed cleaning is not good. When the angle of the seed clearing plate is 8°, there is one seed potato in the seed picking claw, and there is no empty seed phenomenon when the claw reaches the top part. When the angle of the seed clearing plate is 10°, there is empty seed phenomenon. In order to optimize the angle of the seed clearing plate, taking the inclination angle as a factor, the qualification rate and the seed missing rate are indicators to conduct a single-factor experiment. The seed cleaning experiment scheme is shown in Table S1, and the experiment results are shown in Table S1. Variance analysis was conducted for the experiment results in Table S2, and the results were shown in Table S3. According to the analysis in Table S3, the qualification rate and seed missing rate in the response surface model were $p \leq 0.001$, and the non-fitting term was $p > 0.05$, indicating that the regression model was highly fitting. Design-expert software was used to perform multiple-regression fitting for the data, and the regression equations of qualification rate Y_2 and seed missing rate Y_3 are as follows:

$$Y_2 = 1.49583 + 0.11623X_4 - 7.34X_4^2 \quad \text{(Eq. 3)}$$

$$Y_3 = 17.65169 - 3080628X_4 + 0.25942X_4^2 \quad \text{(Eq. 4)}$$

It can be seen from Figure 10 a,b that the angle of the seed clearing plate has an impact on the qualification rate Y_2 and seed missing rate Y_3. The qualification rate increases first and then decreases with the increase of the inclination angle. When the inclination angle is 8°, the qualification rate is the best. The seed missing rate decreases first and then increases with the increase of the inclination angle. When the inclination angle was 8°, the seed missing rate was the lowest. According to the optimization results, when the angle of the seed clearing plate is 7.53°, the qualification rate is 90.1%, and the seed missing rate is 3.7%.

According to the above analysis, the seed picking speed, size of seed picking claw, and angle of seed cleaning plate are the main factors affecting the performance of potato seed-metering devices. In order to obtain a better multi-factor combination parameters to improve the seed metering performance, a simulation orthogonal experiment was needed to carried out.

Orthogonal simulation experiment

Influencing factor

According to the above analysis, seed picking speed, size of seed picking claw, and angle of seed cleaning plate are the main factors affecting the performance of potato seed-metering devices. A multi-factor simulation experiment is carried out in EDEM using the orthogonal experimental method. Three kinds of claws were used, including A (a20, b10, r24), B (a25, b15, r28), and C (a30, b20, r32). To reduce the amount of simulation calculation, the double row was simplified into a single row seed-metering device, and the seed box, seed cleaning plate, seed spoon, and seed guard slot were reserved. $L_9(3^4)$ orthogonal is selected for the simulation experiment, the factor levels are shown in Table S4, and the orthogonal experiment scheme and results are shown in Table S5.

The experiment results of the were analyzed by ANOVA, and the results are shown in Table S6.

Analysis of the influence of factors on indicators

As displayed in Table S6, the effect of seed picking speed X_1 on the seed replaying rate $Y1$ is extremely significant ($p<0.01$). The quadratic terms X_2^2 and X_3^2 of the type of seed picking claw and the angle of the clearing plate has a significant effect on the seed replaying rate ($0.01<p<0.05$). The interaction X_1X_2 between the seed picking speed X_1 and the claw type X_2And the interaction X_2X_3 between the claw type X_2 and the angle of seed clearing plate X_3 have a significant impact on the seed replaying rate ($0.01<p<0.05$). The other factors have no significant effect on the seed missing rate ($p>0.1$). The regression equation of each factor is:

$$Y_1 = -0.84050 - 3.87500X_1 + 1.45750X_2 + 0.61600X_3 — 0.2500X_1X_2 — 1.17129 \times 10^{-4}X_1X_3 — 0.12000X_2X_3 + 8.75X_1^2 + 0.23750X_2^2 — 0.03800X_3^2 \quad \text{(Eq. 5)}$$

As revealed in Table S7, the interaction X_2X_3 between the claw type X_2 and the angle of seed clearing plate X_3 And the angle of the seed clearing plate X_3 have a significant impact on the seed replaying rate (p<0.01). The seed picking speed X_1, the angle of seed clearing plate X_3, the interaction X_1X_2 between the seed picking speed X_1 and the claw type X_2 have a significant impact on the seed replaying rate (0.01<p<0.05). The claw type X_2 has a significant impact on the seed replaying rate (0.01<p<0.05). The other factors have no significant effect on the seed missing rate (p>0.1). The regression equation of each factor is:

$$Y_2 = 4.54040 - 27.57500X_1 - 0.44000X_2 + 1.59020X_3 + 8.75000X_2 — 2.80000 \times X_1X_3 — 0.41000X_2X_3 + 54.000X_1^2 + 0.36500X_2^2 — 0.025600X_3^2 \quad \text{(Eq. 6)}$$

Response surface analysis and parameter optimization

The results were analyzed by Design-Expert 8.0.6 software. Figure 10 demonstrated that seed picking speed, the angle of seed clearing plate, and parameters of seed picking claw all have an impact on the experiment indicators. When the seed picking speed is constant, the seed replaying rate decreases with the increase of the angle of the seed clearing plate, and the seed missing rate increases first and then decreases with the increase of the angle of the seed clearing plate and is optimal value is at 6°~7. When the angle of the seed clearing plate is constant, the seed replaying rate increases with the increase of seed picking speed, and the seed missing rate decreases first and then increases with the increase of seed picking speed and is optimal at 0.4~0.5 m/s. Considering the actual work requirements, the type-B claws are selected, the seed picking speed is 0.5m/s, the angle of the seed clearing plate is 7.5°, the seed replaying rate is 2.5%, and the seed missing rate is 1.6%.

Validation by bench experiment

As revealed in Table S7, in the potato seed row bench experiment, the seed replaying rate is 3.7%, and the seed missing rate is 2.9%, which is slightly different from the seed replaying rate of the simulation experiment, which is 2.5%, and seed missing rate which is 1.6%. During the actual experiment, the difference between simulation and experiment is very small due to the vibration of the chain and the error caused by the uneven potato cutting.

Conclusions

With the help of DEM, the influence of the structural parameters of the claw on the number of seeding was analyzed. When the terminal radian is 32°, the qualification rate of seed picking increases with the increase of vertical spacing and lateral spacing, and the influence of lateral spacing on the indicator is slightly less than that of vertical spacing; When the lateral spacing is 30 mm, and the terminal radian is constant, the qualification rate of seed picking increases first and then decreases with the increase of the vertical spacing. When the vertical spacing is constant, the qualification rate increases first and then decreases with the increase of the terminal radian, and the influence of the terminal radian is slightly less than the longitudinal length of the picking claw; When the vertical spacing is 15 mm, and the terminal radian is constant, the qualification rate increases with the increase of seed picking claw; When the lateral spacing is constant, the qualification rate increases first and then decreases with the increase of the terminal radian. Therefore, it is clear that the size of the construction of the claw has a significant effect on the number of seeds taken.

The influence of seed picking speed on seed filling performance, seed picking speed was studied. There was little difference in the speed between the seed potato on the seed picking claw and the seed potato moving at a low speed nearby. There is an obvious difference between the speed of seed potatoes around the seed picking claw and the speed of the seed potatoes in the population. The state of the potato seeds is unstatutable easily leads to the occurrence of an empty seed phenomenon.

Influence of the angle of seed clearing plate on seed cleaning was analyzed. The angle of the seed clearing plate has an impact on the qualification rate and missed seeding rate. The effect of the angle of the seed clearing plate on seed cleaning was analysed. The angle of the seed cleaning plate has an effect on the qualification rate and the missed seed rate.

According to the above analysis, the seed picking speed, the size of the seed picking claw and the angle of the seed cleaning plate are the main factors affecting the performance of potato seed drills. From this, it is clear that the seed picking speed, the size of the seed picking claw and the angle of the seed cleaning plate are the main factors affecting the performance of potato seed dosing machines, a multi-factor simulation experiment is carried out using the orthogonal experimental method. When the seed picking speed is constant, the repetition rate decreases with the increase of the angle of the seed cleaning plate, and the seed missing rate first increases and then decreases with the increase of the angle of the seed cleaning plate; when the angle of the seed cleaning plate is constant, the repetition rate increases with the increase of the seed picking speed, and the seed missing rate first decreases and then increases with the increase of the seed picking speed.

Acknowledgements

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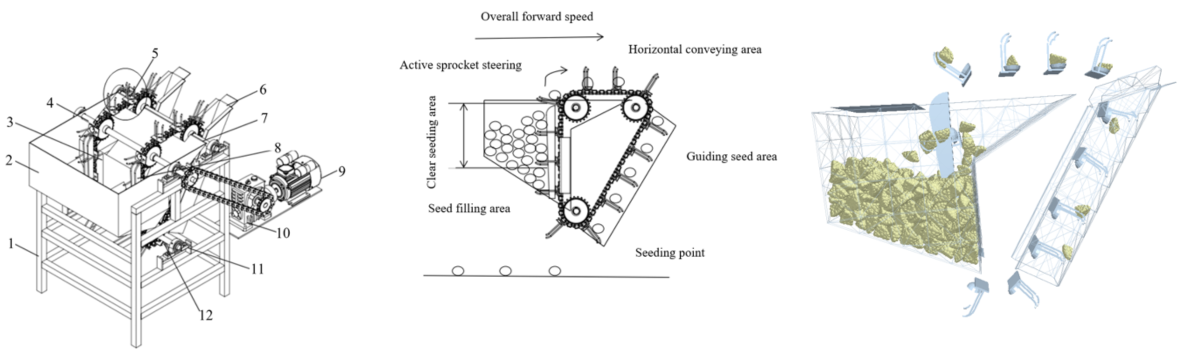
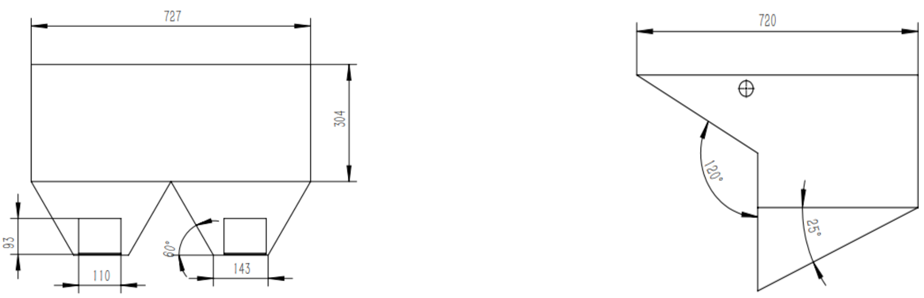
(a) 3D model (b) DEM model

Figure 1. Potatoes model.

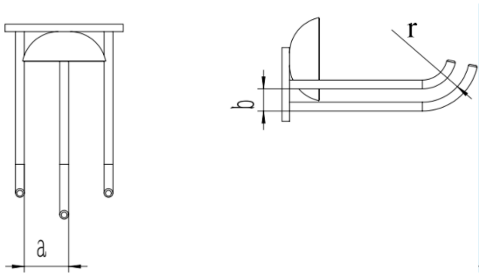


(a) Structural components (b) Seeding principle (c) Seeding simulation model

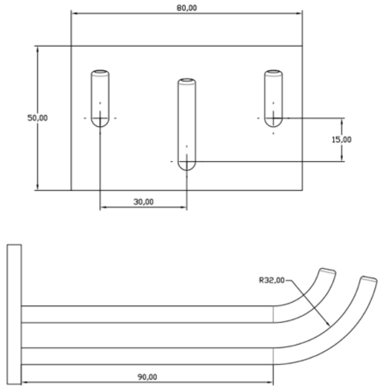


(d) Size of seed box

Figure 2. Main structure of seed metering device. Main structure of seed metering device. 1. frame; 2. seed box; 3. support plate; 4. driving shaft; 5. seed picking claw; 6. seed preventing plate; 7. driven shaft; 8. seed clearing plate; 9. motors; 10. reducer; 11. bearing support; 12. driven shaft

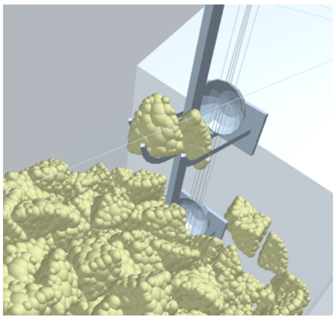


(a) Simulation size parameters

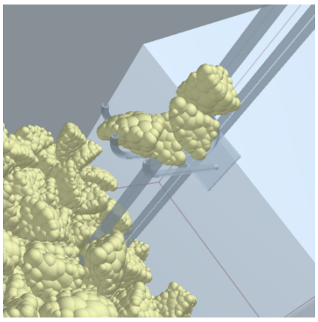


(b) other size

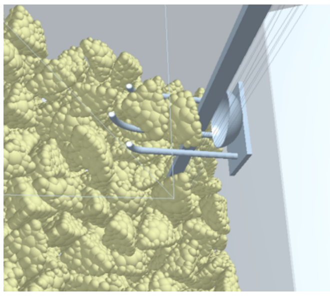
Figure 3. Structural parameters of seed picking claw.



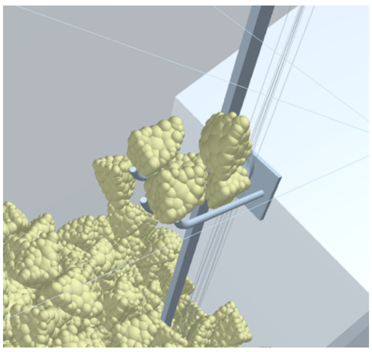
(a) a30, b15, r32



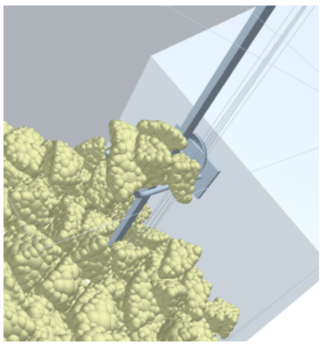
(b) a30, b10, r32



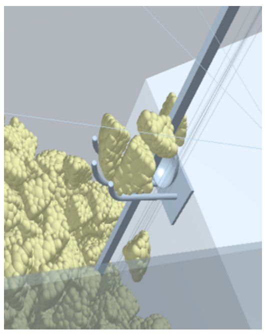
(c) a30, b15, r28



(d) a30, b10, r28



(e) a25, b15, r32



(f) a25, b10, r32

Figure 4. Seed potato picking number of seed picking claw.

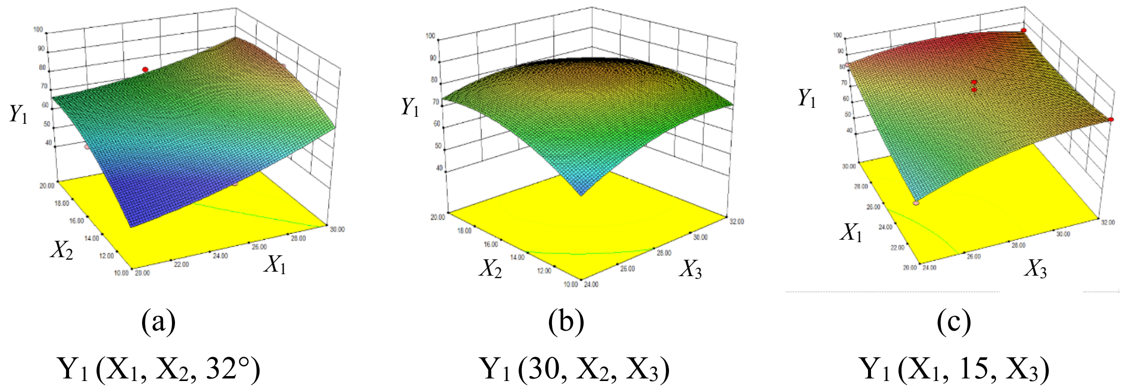


Figure 5. Response surface graph of seed picking experiments.

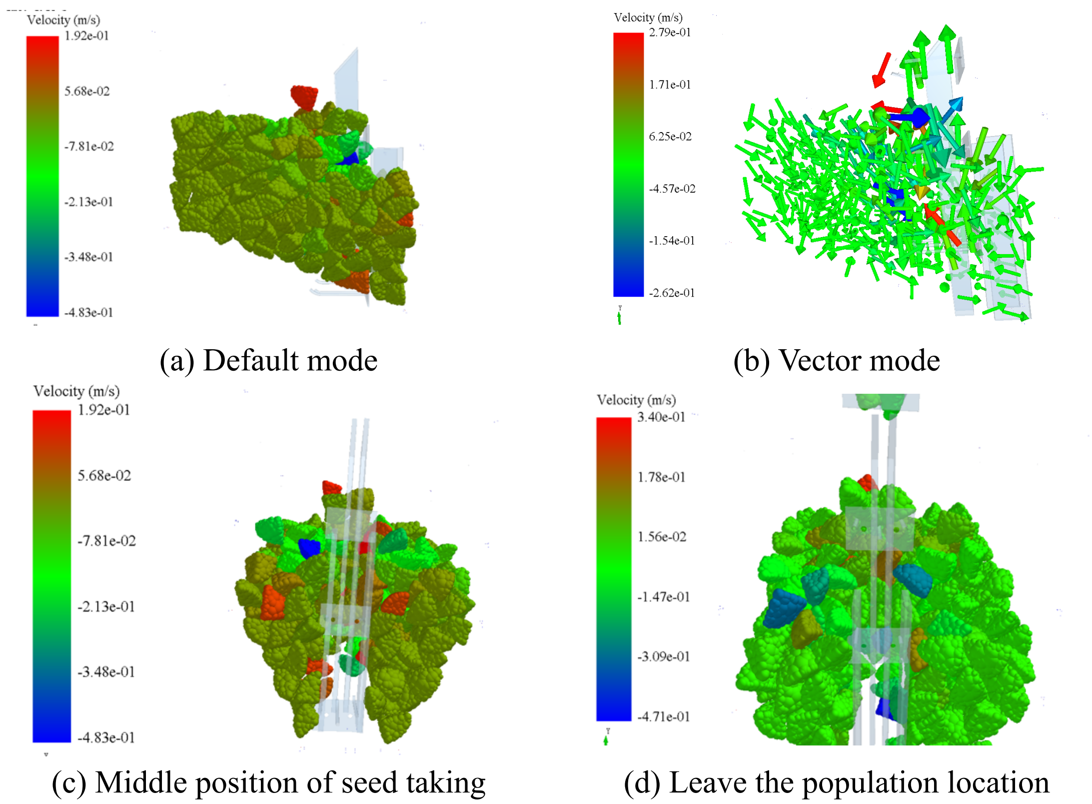


Figure 6. Filling seed number when seed pickup speed is 0.4 m/s.

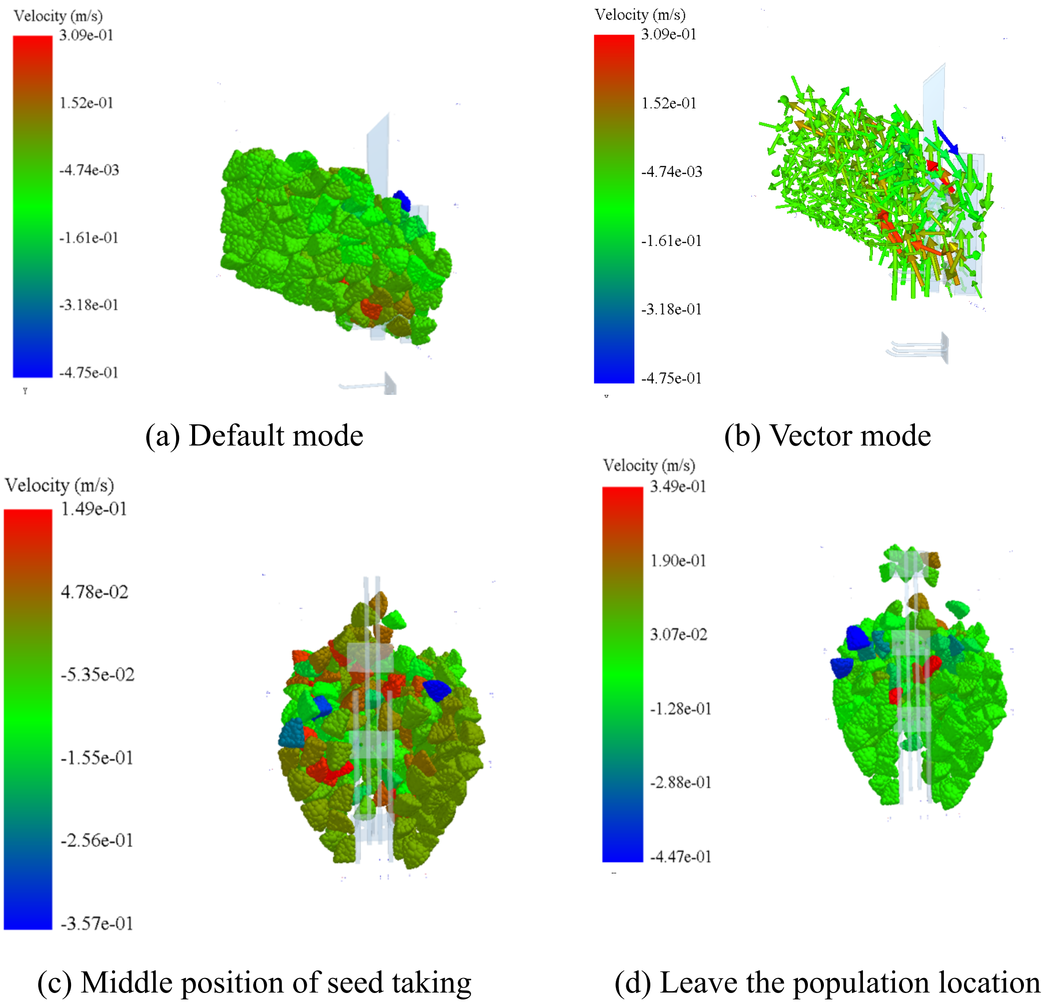
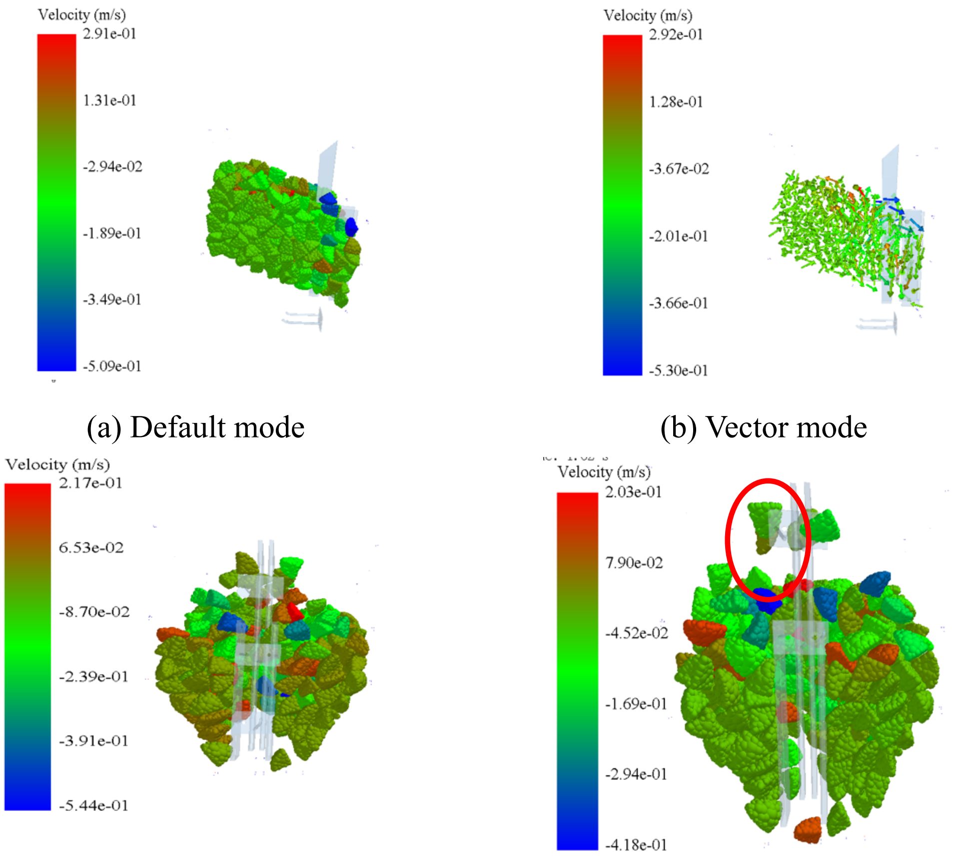
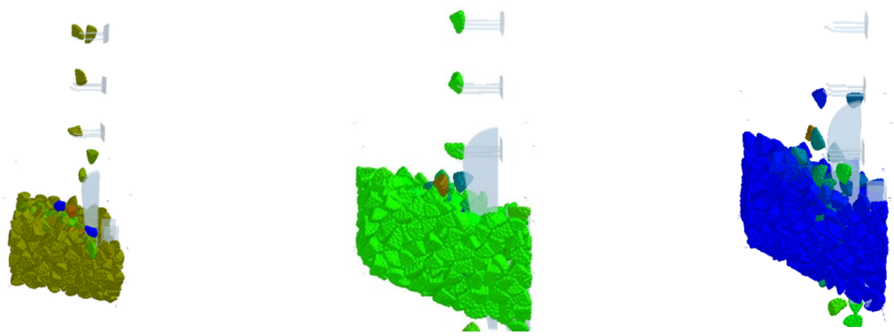


Figure 7. Filling seed number when seed pickup speed is 0.5 m/s.



(c) Middle position of seed taking (d) Leave the population location

Figure 8. Filling seed number when seed pickup speed is 0.6 m/s.



(a) 6° (b) 8° (c) 10°

Figure 9. Clear seeding simulation results in different angles of seed clearing plate.

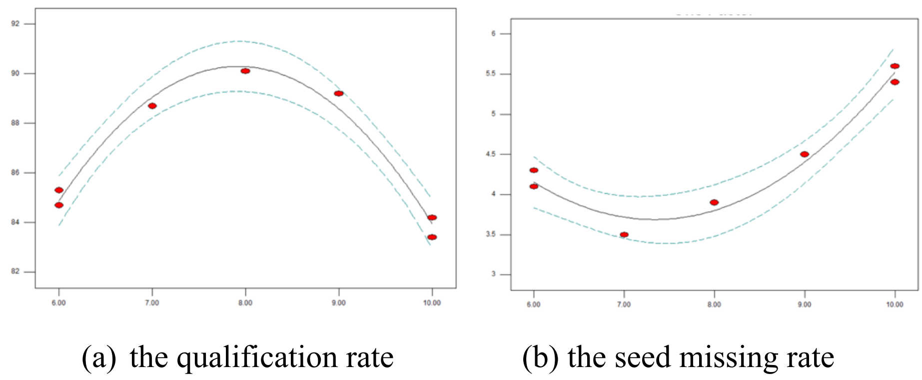


Figure 10. Effect of the angle of the seed clearing plate on the qualification rate and the seed missing rate.

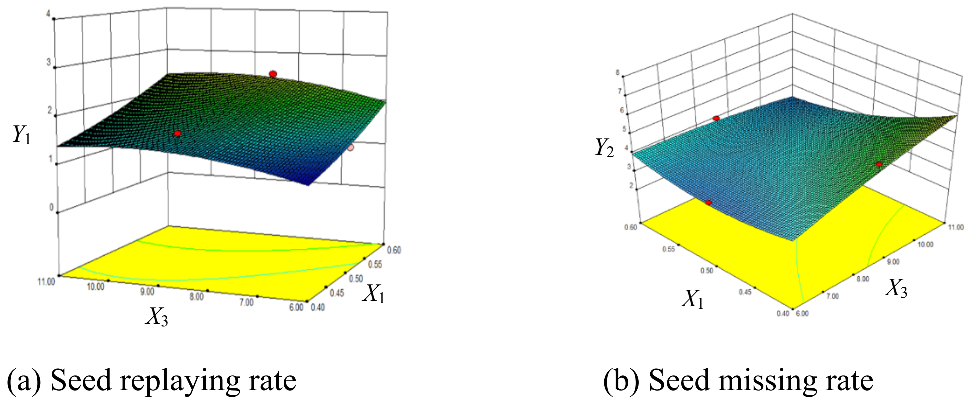


Figure 11. Type of seed claw is type *B*, the influence of factors on the seed replaying rate.

Figure 12. Comparative experiment of potato seed metering device.

Table 1. Simulation parameters of potato seed metering simulation.

Parameter	Value	Resource
Seed potato density(kg/m^3)	1048	Shi *et al*., 2022
Seed potato Poisson's ratio	0.57	Shi *et al*., 2022
Seed potato shear modulus (MPa)	1.34×10^2	Shi *et al*., 2022
Coefficient of restitution between seed potatoes	0.79	Shi *et al*., 2022
Coefficient of static friction between seed potatoes	0.452	Shi *et al*., 2022
Coefficient of rolling friction between seed potatoes	0.024	Shi *et al*., 2022
Steel density (kg/m^3)	7800	EDEM software
Shear modulus of steel (MPa)	7×10^4	EDEM software
Poisson's ratio of steel	0.30	EDEM software
Coefficient of restitution between seed potatoes and steel	0.71	Lv *et al*., 2015
Coefficient of static friction between seed potatoes and steel	0.445	Lv *et al*., 2015
Coefficient of rolling friction between seed potatoes and steel	0.269	Lv *et al*., 2015

Table 2. Experiment factors and levels of seed picking experiments.

Level	Lateral spacing of seed picking claws X_1	Vertical spacing of seed picking claws X_2	Terminal radian X_3
-1	20	10	24
0	25	15	28
1	30	20	32

Table 3. Experimental protocol and results of seed picking experiments.

X_1	X_2	X_3	Y_1
1	-1	0	82.14
-1	-1	0	64.05
-1	1	0	79.43
-1	0	1	84.04
-1	0	-1	60.3
0	0	0	89.52
0	0	0	80.06
0	-1	-1	53.07
0	-1	1	70.3
1	1	0	84.9
0	1	-1	74.06
0	0	0	80.52
0	0	0	85.04
1	0	1	85.53
0	0	0	70.68
0	1	1	75.03
1	0	-1	84.56

Table 4. Analysis of experiment results of seed picking experiments.

Source of variance	Square	Freedom	*F* value	*p*
Model	1422.52	9	5.28	0.0196
X_1	303.96	1	10.16	0.0153
X_2	240.46	1	8.04	0.0252
X_3	230.16	1	7.69	0.0276
X_1X_2	39.82	1	1.33	0.2866
X_1X_3	129.62	1	4.33	0.0759
X_2X_3	66.10	1	2.21	0.1808
X_1^2	50.97	1	1.70	0.2331
X_2^2	207.10	1	6.92	0.0339
X_3^2	153.39	1	5.13	0.0580
Non-fitting term	4.36	3		0.9625
Error	49.10	4		
Sum	1631.99			

$p<0.01$ was considered very significant; $0.01<p<0.05$ was considered significant; $0.05<p<0.1$ was considered less significant.