Optimization of operating parameters of seeding device in plot drill with seeding control system

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Abstract: Plot drill has a significant impact on field breeding by replacing manual seeding. However, the seeding performance of plot drill needs to be further improved as the mechanical transmission method cannot work under the optimal combination of operating parameters. In this study, a cone compartment tray of sowing device was evaluated under the laboratory conditions, using a self-designed seeding control system to adjust the operating parameters. Among them, a plot seeding control system was involved that could set operating parameters through an Android terminal, which effectively reduced the difficulty of parameters adjustment. The method of central composite experiment design was employed to conduct experiments and explore the effects of experiment factors such as lifting height of storage tube (*LHST*), rotation speed of cone compartment tray (*RSCCT*), and rotation speed seed distributor (*RSSD*) on the seeding uniformity coefficient of variation among rows (*SUCVR*) and the rate of damaged seeds (*RDS*). For *SUCVR* of wheat, the results showed that the importance order of main factors from high to low was *RSSD*, *RSCCT* and *LHST*. And for *SUCVR* of buckwheat, *RSCCT* had the largest influence, followed by *RSSD*, and *LHST* had the smallest influence. For *RDS* of wheat and buckwheat, only *RSSD* had a very significant effect among the main factors. The experiments data of wheat indicated that when operated at 27.2 mm for *LHST*, 4.5 r/min for *RSCCT* and 1169 r/min for *RSSD*, the sowing performance of wheat was optimal, with *SUCVR* and *RDS* values of 5.02% and 0.117%, respectively. The buckwheat seeding performance was found to be optimal when the *LHST*, *RSCCT* and *RSSD* were 26.5 mm, 3.9 r/min and 711 r/min, and *SUCVR* and *RDS* were 4.74% and 0.113%. The seeding control system realized the electromechanical control of the seeding equipment, was convenient for parameter setting and stepless adjustment, and could be operated under an optimized combination of operating parameters. The research results could provide a reference for the performance improvement and application of plot drill.

Keywords: plot drill, seeding device, seeding control system, seeding performance, parameter optimization
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1 Introduction

Globally, agricultural grain production increase has helped millions of people to escape poverty and starvation in many countries and regions over the past half century[1]. However, some studies indicate that agricultural grain production will have to be increased substantially to meet the food needs of the increasing population[2]. As one of the main ways for crops high quality and yield, field breeding experiments are important for improving and breeding new crop varieties[3,4]. Filed breeding experiments are small plot trials, whose main goal is to obtain high-quality, high-yield and stable-yielding crop varieties. When each excellent variety is widely applied, the yield increase will grow from 5% to 10%[5].

Plot drill is an important component of field breeding experiment machine that has a significant impact on accuracy and scientificity of trial results[6,7], which can sow the quantitative seeds into plot with specified length and width, and can clean residual seeds[8,9]. Since the 1930s to present, the plot seeding machinery has gone through three stages of preliminary exploration stage, mechanical maturity stage and performance improvement stage. Its technology and equipment has progressed for a long time. In the spring of 1958, the first Oyjord plot seeder was constructed in the workshop of the Norwegian Institute of Agricultural Engineering, which was a symbolic event in the history of plot machine[10]. Since then, plot drill was designed based on this structure. Nowadays, plot drill is developing in the direction of automation and intelligence in developed countries. Plot drills can basically meet the requirements of plot seeding in developing countries, and the seeding performance needs to be further improved.

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To promote the development and application of plot seeders in different countries, researchers have conducted a large number of experimental studies. Richard et al.[11] designed a small-plot seeder and fertilizer applicator based on planter frame of the Hege Equipment Inc to meet objective of multiple cultivar and fertility levels in field experiments. In Egypt, Wael[12] developed and evaluated plot seeder of cone belt, taking wheat, lentil, and flax as the research objects and experiments were conducted through three stages between 2014 and 2016 to apply sowing for different crops. In China, Liu et al.[13] investigated the effect of storing device on the crop seed dispersion uniformity for plot seeder, which selected five kinds of seed (black sesame seed, Chinese cabbage seed, rape seed, wheat seed and soybean seed) to improve the adaptability of storing device.

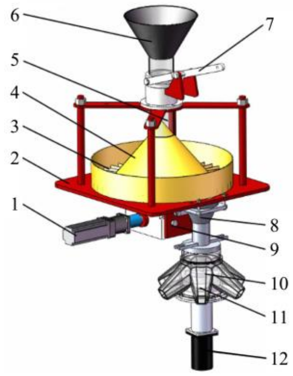
At present, cone compartment tray seeding meter is the most commonly used form of seed metering device for plot seeder, and it can complete the seeding of a plot by rotating one circle. The movement of cone compartment tray seeding meter is obtained from the ground wheel or drive wheel by mechanical drive components (such as chain sprockets and gears), which is similar to the field planter[14]. So, the transmission ratio needs to be adjusted to reach the requirements of different seeding lengths. This transmission method is susceptible to the influence of field soil and has some shortcomings which are inevitable. When the motion is transmitted from the ground wheel or drive wheel to the seeding device, undesired situations may occur, such as ground wheel slippage and sprocket vibration, which will reduce the seeding performance of plot drill. Due to mechanical transmission systems is not easy to adjust, seeding device of plot drill cannot operate under the conditions of best combination of operating parameters, and its seeding performance cannot be guaranteed. These negative factors limit the application of plot drill.

In order to solve the shortcomings mentioned above, researchers have made some efforts in the development of electromechanical control system which uses step or direct current (DC) motor to improve the precision and efficiency of plot drill[15] . However, electromechanical control system still fails to achieve convenient adjustment of operating parameters and human-computer interaction in practical applications. So, the present study was conducted to solve low performance of mechanical transmission systems and obtain appropriate combination of operating parameters by (1) developing a practical and cost-effective seeding control system for plot drill; (2) conducting experiments to evaluate the effect of operation parameters on working performance for wheat and buckwheat under laboratory controllable conditions; (3) establishing a mathematical model of the operating parameters and optimizing of parameter combinations.

2 Materials and methods

2.1 Seeding device description

In this study, the structure of seeding device of plot drill is shown in Figure 1. It consisted of storage tube, lifting leverage, cone compartment tray seeding meter, gear box, seed distributor, and seeding control system. This device can complete storage, falling, transportation and distribution of seeds. Among these components, a pair of bevel gears in the gear box was used to convert horizontal rotation into vertical rotation. Cone compartment tray seeding meter was one of the most important parts of seeding device and was composed by cone and compartment tray. The seeding port was arranged on the bottom plate of cone compartment tray seeding meter so that the seeds can drop into the distributing area under the action of gravity. The seed distributor was installed below seeding port and was connected to 6 rows of tubes. Due to the particularity of the pot seeding, the cone compartment tray seeding meter and the seed distributor were the core of whole seeding device, and were also the main distinctions from traditional seeding mechanical. The cone compartment tray was driven by stepper motor, had adjustable rotating speed and maximum torque was 4 N·m. The seed distributor was driven by brushless DC motor with a speed range of 0-3000 r/min. The length, width and height of seeding device were 0.68 m, 0.45 m and 1.04 m, respectively. And, the diameter of storage tube was 70 mm, the number of panels was 42, and the angle of cone was 50°.



1. Stepper motor 2. Bottom plate 3. Compartment tray 4. Cone 5. Storage tube 6. Collection funnel 7. Lifting leverage 8. Gathering tube 9. Gear box 10. Seed distributor 11. Six-row split tube 12. Brushless DC motor

Figure 1 Cone compartment tray seeding device structure

2.2 Seeding control system

Different from the mechanical transmission systems, the designed seeding control system was composed of Android terminal, main controller, control module of cone compartment tray seeding meter, control module of seeder distributor, and power, as shown in Figure 2. In the laboratory, power module provided power for the entire seeding control system. The seeding control system applications was installed on the Android terminal with user-friendly human-computer interaction interface, which mainly completed communication with main controller and parameter settings such as rotation speed of cone compartment tray (*RSCCT*) and rotation speed of seed distributor (*RSSD*). Furthermore, the seeding control system application had a wide range of adaptability and can be installed on any Android device with Bluetooth. STM32 single-chip microcomputer (ST Microelectronics, Italy) was used as the main controller of seeding control system, which was to receive and process data from the Android terminal and to achieve the rotation speed adjustment of cone compartment tray and seed distributor by using pulse width modulation (PWM) technique. The communication connection between Android terminal and main controller was established by Bluetooth transmission. The rotational speed of stepper motor was transferred to cone compartment tray seeding meter via a pair of bevel gears. The rotational speed transmission between brushless DC motor and seeder distributor was completed by coupling and drive shaft.

The working flow diagram of the seeding control system is depicted in Figure 3. At the beginning, a certain amount of seeds were poured into seed storage space formed by storage tube and cone. The operator opened the developed software program and established a communication connection between the Android terminal and main controller, and then input parameters of *RSCCT* and *RSSD* into the human-machine interaction interface. After receiving the parameters, the main controller calculated target value of *RSCCT* and *RSSD* and determined the frequency and duty cycle of the required pulse signal. Finally, the rotation speed control instructions were sent to the speed driver to adjust the speed of stepper motor and brushless DC motor, respectively. When seeding device was operating normally, operator pressed lifting leverage to make storage tube be lifted upwards, and seeds slid down along cone and were evenly distributed to compartment tray space. With the rotation of cone compartment tray, the seeds were pushed through the sowing port to form a uniform seed flow. Then, seeds dropped into seed distributor and were evenly distributed into each row of tubes under the centrifugal action of high-speed. The plot seeding device adopting the control system could easily adjust the parameters of *RSCCT* and *RSSD*, and adapt to different seeding requirements.

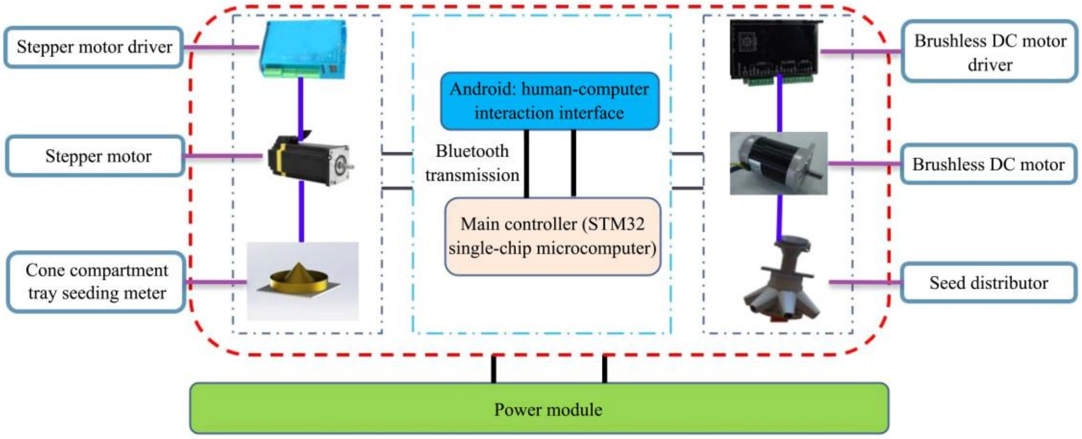


Figure 2 Components of seeding control system

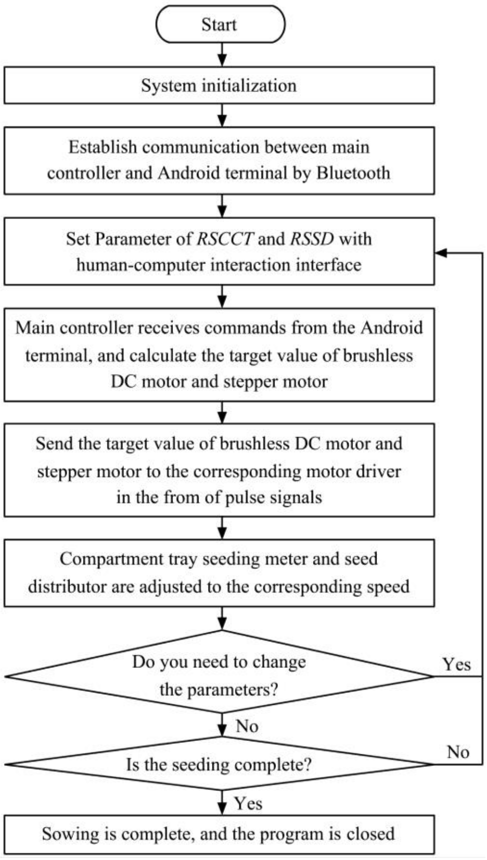


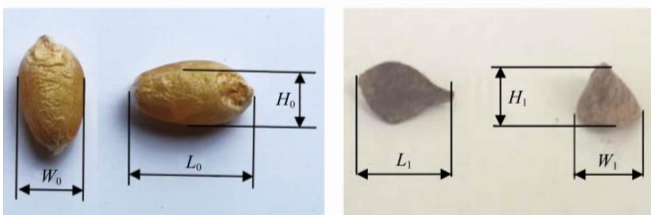
Figure 3 Working flow diagram of the seeding control system

As we known, there were few studies on plot seeding machinery because of its particularity and narrow application range. During the experimental research on field machinery, it was founded that mechanical driving methods had different degrees of slip that affected the seeding performance[16,17]. For the plot drill, there was also the problem of the mechanical drive system slipping. Therefore, an seeding control system that the seeding device was driven by motor was developed to replace the mechanical drive system[18], which can effectively reduce the negative slippage. And, this paper carried out a experimental research on the optimization of plot seeding operation parameters to improve seeding performance based on the control system.

2.3 Bench experiments under laboratory conditions

2.3.1 Seeds comparison

The seeds of wheat and buckwheat were researched as subjects, and their shapes were different (Figure 4). Before the experiments, 30 seeds of each variety were randomly selected, and main dimensions were measured. For wheat (Figure 4a), its shape was long oval. The range of length (L_0), width (W_0), and thickness (H_0), were 5.18-6.83 mm, 2.61-3.52 mm, and 2.21-3.49 mm respectively, and mean value were 6.19, 3.25 and 2.89 mm. As a kind of cash crop, buckwheat has great edible and medicinal value. The shape of the buckwheat was more special that edges and corners were more distinct, and it had a triangular shape (Figure 4b). Length (L_1), width (W_1) and thickness (H_1) of buckwheat ranged from 4.91 to 7.00 mm, 3.19 to 4.97 mm and 2.98 to 4.33 mm respectively, and mean values were 5.93, 3.94 and 3.72 mm.

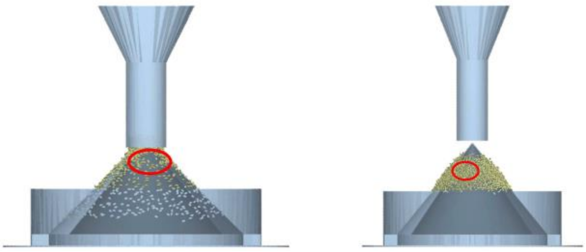


a. Wheat b. Buckwheat

Figure 4 Seeds shape and size

2.3.2 Experiment factors and design

Lifting height of storage tube (*LHST*): Seeds falling refers to the process seeds falling from the seed storage tube into the cone compartment tray, which is one of the key links of plot seeding operation. The *LHST* has an important influence on the consistency of seeds number sliding down along cone and falling into cone compartment tray, thus affecting uniformity of seeding. If *LHST* is too small, there will be problems such as poor flow of seed along the cone, easy to be stuck, which will eventually lead to long falling time and poor uniformity (Figure 5a). Although some problems can be avoided, new problems will appear at a larger *LHST* that top layer collapses and mutual interference happens between the seeds, which affects seeding uniformity (Figure 5b).



a. Small *LHST* b. Larger *LHST*

Figure 5 State of seeds falling under different values of *LHST*

Therefore, to assess the impact of *LHST* on the seeding performance, *LHST* was chosen in the range of 14-36 mm for the orthogonal rotation combination experiments according to seed size and pre-experiment.

Rotation speed of cone compartment tray (*RSCCT*): The *RSCCT* is one of key operating parameters of plot seeding, and has a great impact on the process of seed falling and distributing. In the process of seed falling, *RSCCT* cause seed to have a certain offset, which will affect the uniformity when entering the cone compartment tray. And, the number of seeds per unit time and the speed of seeds entering distribution area gradually increase with the *RSCCT* increase. In this case, the disorder of seeds appears to become larger, and the pressure of distributing has increased. However, when the *RSCCT* is low, the small amount of seeds per unit time will still affect the uniformity of seeding, and the operating efficiency cannot meet the requirements. The number of seeds per unit time (m) and the speed of seed entering distribution area (v) were calculated from the equations below.

$$\begin{cases} m = \dfrac{M_0 \cdot n}{60} \\ v = \sqrt{{v_y}^2 + {v_x}^2} = \sqrt{g^2 t^2 + \dfrac{\pi^2 n^2 r^2}{900}} \end{cases} \tag{1}$$

where, m is the number of seeds per unit time, grains/s; M_0 is the total number of seeds; n is the *RSCCT*, r/min; v is the speed of seeds of entering distribution area, m/s; v_y is the sub-velocity in the vertical direction, m/s; v_x is the sub-velocity in the horizontal direction, m/s; g is the acceleration of gravity, m/s^2; t is the time to enter distributing area from the cone compartment tray, s; r is the radius of cone compartment tray, m.

As the driving speed of plot drill was 0.4-1 m/s, seeding length of plot was 2-10 m generally and maximum seeding length of some plot trials could reach 32 m, *RSCCT* was selected in the range of 2.5-9.5 r/min combining the pre-test results of previous period and taking into account the operating efficiency of plot drill.

Rotation speed of seed distributor (*RSSD*): Seed distribution by seed distributor is last step in the seeding operation, which directly determines consistency of number of seeds in each row. Taking a single particle as an example, the seeds distributing process is shown in Figure 6 at the ideal conditions. At the action of high-speed rotation of the seed distributor, the seed particle gradually moves from the initial position A to the position B on the edge of the distributor, and finally leaves the distributing area.

In the previous theoretical analysis, it can be known that as the rotation speed of seed distributor increases, the linear velocity of the seeds thrown out by the centrifugal force gradually increases. When the *RSSD* is small, the centrifugal linear speed is not enough to spin out seeds quickly, and the subsequent falling of seeds will affect previous seeds, resulting in poor distribution effect. On the contrary, seeds will also be unevenly distributed and seeds damage may increase at the large of *RSSD*. Therefore, according to the pre-experiment, and comprehensively considering the seeding uniformity and seed damage, this paper selected the *RSSD* of wheat at 1000-1500 r/min and the buckwheat *RSSD* range of 650-950 r/min to study the influence on the uniformity of seeding.

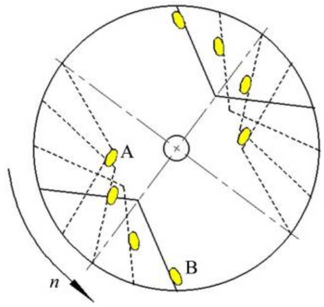


Figure 6 Process of seeds distributing

Experiment design: In the actual sowing operation, the structure parameters of plot seeding device are fixed, and it is unlikely to replace key structure of different parameters to meet the requirements of different varieties. So, *LHST*, *RSCCT* and *RSSD* are variable operating parameters when the structural parameters are fixed to achieve better seeding quality. They have a direct impact on seeding performance and are extremely important. So, in order to obtain a better combination of operating parameters, the experiments were conducted under the laboratory conditions at China Agricultural University using the cone compartment tray of sowing device (Figure 7) by Menoble Co., Ltd. (Beijing, China), and the matching seeding control system was used.

Figure 7 Test bench of plot seeding

In this paper, a three-factor five-level response surface optimization experiment was conducted by using the central composite design (CCD) of Design Expert 8.0.6 (Stat-Ease, United States). This experiment had 23 groups in total, and each group of experiment was repeated three times. Experimental factors and levels are shown in Table 1.

Table 1 Experimental factors and levels

Levels	Factors			
	X_1/mm	X_2/r·min^{-1}	X_3(wheat)/r·min^{-1}	X_3(buckwheat)/r·min^{-1}
$+\gamma$	36.0	9.5	1500	950
+1	31.5	8.1	1399	889
0	25.0	6.0	1250	800
–1	18.5	3.9	1101	711
$-\gamma$	14.0	2.5	1000	650

Note: γ represents 1.682; X_1 represents *LHST*; X_2 represents *RSCCT*; X_3 represents *RSSD*.

2.3.3 Experiment evaluation indicators

To evaluate the performance of seeding device, seeding uniformity coefficient of variation among rows (*SUCVR*) and rate of damaged seeds (*RDS*) were selected as evaluation indicators. Each row of seeds must be collected separately at the end of experiment. Each outlet of seed distributor was equipped with a seed bag which could avoid seed dispersion and was beneficial to seed statistics and analysis. Significance analyses in this study were conducted using Design-Expert.V8.0.6 and analysis of variance (ANOVA) was used for assessing seeding effects.

SUCVR was employed for assessing the consistency and uniformity of the seeding rate each row. When the *SUCVR* value was large, the results indicated that the seeding device could not work well and the seeding consistency was poor. Calculation equation of the *SUCVR* (C_v) was shown in Equation (2).

$$Cv = \frac{1}{u}\sqrt{\frac{\sum_{i=1}^{n}(m_i - u)}{n_r - 1}} \times 100\% \qquad (2)$$

where, u *is* the mean number of seeds in each row, m_i is the number of seeds in the ith row and n_r is the total number of rows.

RDS was also one of the key indicators reflecting the performance of seeding. At the end of each experiment, researchers needed to observe and select seeds, collecting the broken seeds. The *RDS* (Y) index was defined as:

$$Y = \frac{M}{M_0} \times 100\% \qquad (3)$$

where, Y is rate of damaged seeds, %; M_0 is the total number of seeds; M is the number of damage seeds.

3 Results and discussion

3.1 Laboratory experiment results

The test results were recorded, and the average value of each group of experiments was calculated after the experiment was completed. The results of *SUCVR* and *RDS* obtained from the experiments for wheat and buckwheat are shown in Figures 8 and 9. These figures showed that the *SUCVR* was less than 10% and the *RDS* was less than 0.5%. It was clear that the highest of *SUCVR* of wheat (6.65%) was in the third group of experiments and the lowest (4.82%) was in the 20th group of trials. For buckwheat, the highest *SUCVR* (6.34%) was in the 10th group of experiments and the lowest *SUCVR* (4.69%) was the test of 17th group tests. The *RDS* of wheat ranged between 0.083%-0.2% with an average value of 0.125%, slightly lower than the *RDS* of buckwheat that was 0.083%-0.233% with an average value of 0.146%.

3.2 Statistical analysis of experiment results

3.2.1 Impact of *SUCVR* indicator

In order to determine the influence of experimental factors on *SUCVR*, Design-Expert was used to perform significance analyses and multivariate regression fitting analysis on the experiment results. ANOVA was repeated after removing the nonsignificant terms of sources, as shown in Tables 2 and 3.

From the ANOVA results of wheat, Table 2 showed that X_2 (p=0.0037<0.01) and X_3 (p=0.0026<0.01) had a very significant effect on *SUCVR*, and X_1 (0.05<p=0.0710<0.1) had a certain effect. It also showed a very significant interaction between X_2 and X_3 (p=0.0011<0.01). In addition, the X_1^2 and X_3^2 also had a very significant effects and X_2^2 had a certain effect. Comparing the size of the p value, the importance order of main factors could be obtained as X_3, X_2 and X_1. The mathematical modeling was established by experimental data, taking into account the X_1, X_2, and X_3. So, the results for *SUCVR* (C_{v1}) of wheat could be expressed by the following regression equations:

$$C_{v1}=20.81245-0.24124X_1+1.14919X_2-0.024284X_3-1.09859E^{-3}X_2X_3+4.43634E^{-3}X_1^2+0.02758X_2^2+1.17182E^{-5}X_3^2 \qquad (4)$$

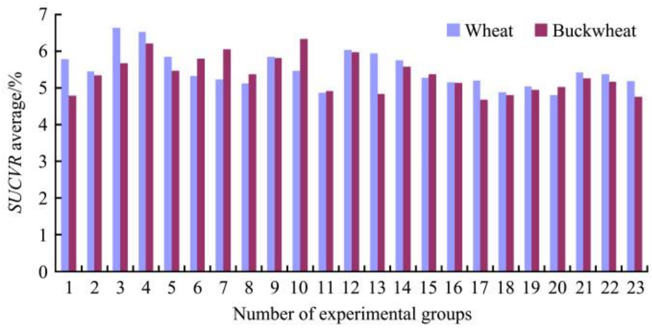


Figure 8 Results of seeding uniformity coefficient of variation among rows (*SUCVR*) obtained from experiments

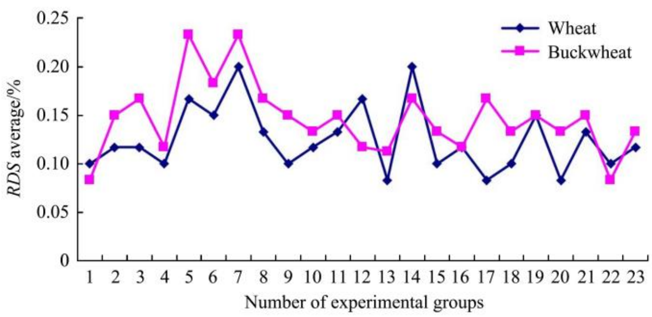


Figure 9 Results of rate of damaged seeds (*RDS*) obtained from experiments

Table 2 ANOVA of *SUCVR* for wheat

Source	Sum of squares	df	Mean square	F value	p value	Significance
Model	4.45	7	0.64	10.97	<0.0001	significant
X_1	0.22	1	0.22	3.78	0.0710	(*)
X_2	0.68	1	0.68	11.79	0.0037	**
X_3	0.76	1	0.76	13.04	0.0026	**
$X_2 X_3$	0.95	1	0.95	16.32	0.0011	**
X_1^2	0.57	1	0.57	9.83	0.0068	**
X_2^2	0.23	1	0.23	3.94	0.0656	(*)
X_3^2	1.07	1	1.07	18.43	0.0006	**
Residual	0.87	15	0.058			
Lack of fit	0.53	7	0.075	1.75	0.2240	not significant
Error	0.34	8	0.043			
Total	5.32	22				

Note: ** means that experiment factor has a very significant effect on the results (p<0.01); * means that experiment factor has a significant effect on the results (0.01<p<0.05); (*) means that experiment factor has a certain impact on the results (0.05<p<0.1), but its significance is not as important as the previous two cases. X_1 represents *LHST*; X_2 represents *RSCCT*; X_3 represents *RSSD*.

Table 3 ANOVA of *SUCVR* for buckwheat

Source	Sum of squares	df	Mean square	*F* value	*p* value	Significance
Model	4.54	7	0.65	11.04	<0.0001	significant
X_1	0.19	1	0.19	3.19	0.0945	(*)
X_2	1.00	1	1.00	17.06	0.0009	**
X_3	0.27	1	0.27	4.62	0.0483	*
$X_1 X_3$	0.26	1	0.26	4.41	0.0530	(*)
$X_2 X_3$	0.33	1	0.33	5.58	0.0321	*
X_1^2	2.16	1	2.16	36.82	<0.0001	**
X_2^2	0.34	1	0.34	5.79	0.0295	*
Residual	0.88	15	0.059			
Lack of fit	0.41	7	0.059	1.01	0.4863	not significant
Error	0.47	8	0.058			
Total	5.42	22				

Note: ** means that experiment factor has a very significant effect on the results ($p<0.01$); * means that experiment factor has a significant effect on the results ($0.01<p<0.05$); (*) means that experiment factor has a certain impact on the results ($0.05<p<0.1$), but its significance is not as important as the previous two cases. X_1 represents *LHST*; X_2 represents *RSCCT*; X_3 represents *RSSD*.

Further analysis of interaction items between X_2 and X_3 is provided in Figure 10. When the range of the X_3 was 1101-1250 r/min, as the X_2 increased from 3.9 to 8.1 r/min, *SUCVR* gradually increased, and the rate of increase was greater near 1101 r/min because the low-speed of seed distributor could not separate the seeds quickly. When the range of X_3 was 1250-1399 r/min, SUCVR first decreased and then increased with the increase of X_2. It was clear that *SUCVR* value decreased first and then increased with the X_3 increasing when X_2 was in the range of 3.9-7.7 r/min, but *SUCVR* had a negative correlation with X_3 when X_2 was in the range of 7.7-8.1 r/min.

Similar information was obtained for buckwheat by Table 3. X_2 (p=0.0009<0.01) had a very significant influence on *SUCVR*, X_3 (0.01<p=0.0483<0.05) had a significant effect on *SUCVR*, which was different from wheat, and X_1 (0.05<p=0.0945<0.1) had a certain impact on *SUCVR*. So, X_2 had the largest influence, followed by X_3, and X_1 had the smallest influence. For the interaction terms, interaction effects of X_2 and X_3 (0.01<p=0.0321<0.05) had a significant effect on *SUCVR*, and interaction effects of X_1 and X_3 (0.05<p=0.0530<0.1) had a certain influence on *SUCVR*. It could be found that X_1^2 (p<0.0001) had a very significant influence on *SUCVR* and X_2^2 (0.01<p=0.0295<0.05) had a significant influence. The regression equation of the relationship between the *SUCVR* of buckwheat (C_{v2}) and the operation parameters was as follows:

$$C_{v2}=-2.2347-0.16551X_1+0.59247X_2+0.015862X_3-3.1115E^{-4}X_1X_3-1.08347E^{-3}X_2X_3+8.648E^{-3}X_1^2+0.033651X_2^2 \quad (5)$$

For the *SUCVR* of buckwheat, Figure 11a revealed the response surface of interaction between X_1 and X_3 under X_2 was 6 r/min. Within the range of 18.5-30.0 mm of X_1, value of *SUCVR* gradually increased with increasing of X_3 from 711 to 889 r/min. And as the value of X_1 increases, the degree of increase in *SUCVR* gradually decreases. In the interval of X_1 of 30.0-31.5 mm, *SUCVR* changed from increasing to decreasing with the X_3 increasing, and the degree of decrease became larger. In all cases, when the X_3 was constant, *SUCVR* initially decreased and then increased as the X_1 increased.

The response surface of interaction between X_2 and X_3 to *SUCVR* of buckwheat is shown in Figure 11b. The rule was observed that *SUCVR* value increased with the increase of X_2 in the X_3 range of 711-807 r/min. Different trends were obtained in the X_3 range of 807-889 r/min that *SUCVR* gradually decreased at first, and then increased after decreasing to a certain value. The results also indicated that when X_2 was in the range of 3.9-7.45 r/min and 7.45-8.1 r/min, the *SUCVR* showed two different trends with the increasing of X_3. In the former interval, as the X_3 increased, the *SUCVR* continued to increase, and increasing trend gradually slowed down. In the latter interval, *SUCVR* gradually decreased as the X_3 increased.

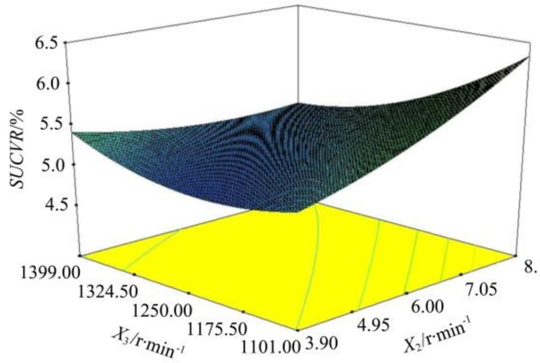
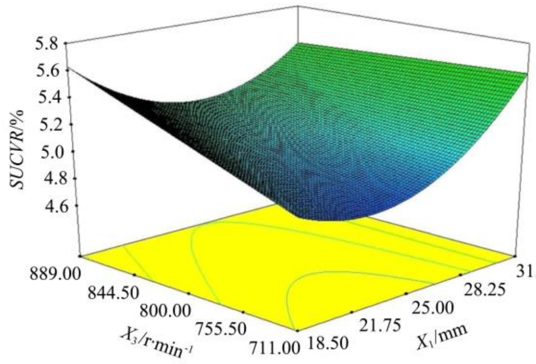
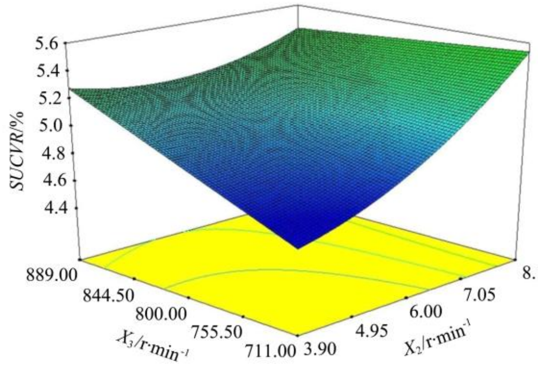


Figure 10 Response surface of interaction between *RSCCT* (X_2) and *RSSD* (X_3) to *SUCVR* of wheat under *LHST* (X_1) of 25 mm



a. Interaction term between *LHST* (X_1) and *RSSD* (X_3) under *RSCCT* (X_2) of 6 r/min



b. Interaction term between *RSCCT* (X_2) and *RSSD* (X_3) under *LHST* (X_1) of 25 mm

Figure 11 Response surface of the interaction term that affects the *SUCVR* of buckwheat

A comprehensive analysis of this study found that comparison with *RSCCT* and *RSSD*, *LHST* had a smaller impact on the seeding performance. But, *LHST* was a factor affecting seed sliding motion status, which was mainly manifested in the interruption or collapse of the seed layer, and could not be ignored. Improper *LHST* would make the dispersibility of the number of seed particles between compartment tray, resulting in uneven numbers of successively entering the distributing area, and thus causing uneven seeding. So, for different seed shapes and sizes, the Discrete

Element Method (DEM) can be used for simulation experiments to determine the appropriate *LHST*. The results of Yang et al.[19] and Liu et al.[20] also proved this view.

RSCCT and *RSSD* were very important factors that affect the seeding performance of plots for wheat and buckwheat. The change of *RSCCT* affects the number of seed grains in a unit time and speed of seeds falling into the distributing area, thereby affecting the uniformity of seeding. *RSCCT* and *RSSD* should be matched with each other, and change synchronously to achieve better seeding performance. When the *RSSD* was constant, as the *RSCCT* increased, the amount of seeding per unit time increased, and seeds would affect each other and could not be separated into the seed tube in time, resulting in poor seeding uniformity. In the case of a small *RSSD*, due to the small number of seeds, it was impossible to form a uniform seed flow into different seed tubes in sequence, resulting in large differences in the number of seeds for different seed tubes.

3.2.2 Impact of *RDS* indicator

The *RDS* is an important index of seeding performance of plot seeder. It can also directly reflect the performance of operation. There are many factors that affect the *RDS*, and this paper only explored from the aspects of operating parameters. Using Design-Expert to carry out regression fitting analysis on the results of *RDS*, it was found that wheat *RDS* was significant in the quadratic regression analysis, while buckwheat *RDS* was significant under the linear regression fitting model. The ANOVA results are shown in Table 4 and Table 5.

Table 4 ANOVA of *RDS* for wheat

Source	Sum of squares	*df*	Mean square	*F* value	*p* value	Significance
Model	0.018	4	4.580E^{-3}	11.36	<0.0001	significant
X_2	3.895E^{-4}	1	3.895E^{-4}	0.97	0.3388	-
X_3	0.012	1	0.012	30.92	<0.0001	**
$X_2^{\ 2}$	3.366E^{-3}	1	3.366E^{-3}	8.35	0.0098	**
$X_3^{\ 2}$	2.103E^{-3}	1	2.103E^{-3}	5.21	0.0348	*
Residual	7.260E^{-3}	18	4.033E^{-4}			
Lack of fit	3.280E^{-3}	10	3.280E^{-4}	0.66	0.7361	not significant
Error	3.980E^{-3}	8	4.974E^{-4}			
Total	0.026	22				

Note: ** means that experiment factor has a very significant effect on the results (p<0.01); * means that experiment factor has a significant effect on the results (0.01<p<0.05); (*) means that experiment factor has a certain impact on the results (0.05<p<0.1), but its significance is not as important as the previous two cases. X_1 represents *LHST*; X_2 represents *RSCCT*; X_3 represents *RSSD*.

Table 5 ANOVA of *RDS* for buckwheat

Source	Sum of squares	df	Mean square	*F* value	*p* value	Significance
Model	0.012	3	4.112E^{-3}	4.24	0.0187	significant
X_1	1.189E^{-3}	1	1.189E^{-3}	1.23	0.2817	-
X_2	2.951E^{-5}	1	2.951E^{-5}	0.030	0.8633	-
X_3	0.011	1	0.011	11.48	0.0031	**
Residual	0.018	19	9.689E^{-4}			
Lack of fit	0.014	11	1.265E^{-3}	2.25	0.1291	not significant
Error	4.490E^{-3}	8	5.612E^{-4}			
Total	0.031	22				

Note: ** means that experiment factor has a very significant effect on the results (p<0.01); * means that experiment factor has a significant effect on the results (0.01<p<0.05); * means that experiment factor has a certain impact on the results (0.05<p<0.1), but its significance is not as important as the previous two cases. X_1 represents *LHST*; X_2 represents *RSCCT*; X_3 represents *RSSD*.

Analyze the experiment results, X_1 and X_2 had no effect on the *RDS* of wheat and buckwheat. The result of ANOVA indicated that only X_3 had a very significant effect on *RDS* among the main factors. This conclusion was advantageous that if a larger *RDS* occurred, X_3 would be required to change to reduce *RDS*. The interactions between factors had no significant effect on the *RDS*.

Stepwise elimination method was used to get regression response surface equation of factors for wheat *RDS* (Y_1):

$$Y_1=0.77324–0.03762X_2–1.0973E^{-3}X_3+3.34772E^{-3}X_2^{\ 2}+5.20127E^{-7}X_3^{\ 2} \tag{6}$$

The regression equation of buckwheat *RDS* (Y_2) was as follows:

$$Y_2=–0.070059–1.4319E^{-3}X_1–7.02576E^{-4}X_2+3.20307E^{-4}X_3 \tag{7}$$

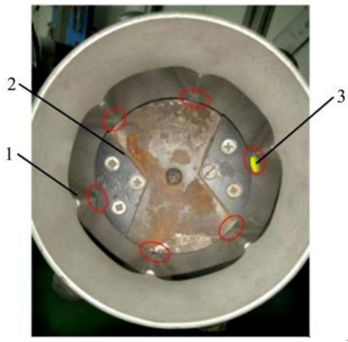
The seeds were collected and observed after the experiment. It was found that both wheat and buckwheat showed different *RDS*. Among them, the number of damaged wheat in each trial was between 1 and 5, and number of damaged buckwheat seeds was 1-7, as shown in Figure 12. Overall observation found that *RDS* of buckwheat was greater than that of wheat. This was because the crushing force of buckwheat was lower than the crushing force of wheat, and buckwheat was more prone to grain damage.

a. Wheat

b. Buckwheat

Figure 12 Damaged seeds in the experiment

There may be two main reasons for seed damage. On the one hand, as the increase of *RSSD*, the linear speed of seed distribution gradually increased, and the collision force of seeds was also greater. When the collision force exceeded crushing force of the seed, seed would be damaged. On the other hand, as shown in Figure 13, there was a certain gap between seed distributor and six-row split tube wall[21]. If seed was in this gap after distributing, as shown in the position of the yellow particles, high speed of seed distributor and V-shaped split tube of six-row formed squeezed and sheared force on the grain, resulting in seed damage. Mechanical damage was the main factor causing seed damage, and Liao et al.[22] also conducted a similar study. The processing and assembly accuracy of machine was closely related to this gap.



1. Six-row split tube wall 2. Seed distributor 3. Seed

Figure 13 Seeds entering gap (shown with red circle) between seed distributor and six-row split tube wall

It should be noted that seed damage includes external and internal damage[12]. External damage is visible and can be determined by observing seeds after sowing. The internal damage is invisible and needs be determined by germination tests. Since plot seeding is used to breed new varieties of crops, seeds are relatively scarce and precious in breeding trials, and seeds should be broken as little as possible.

3.3 Optimization of parameter and verification

To get the optimal performance parameters of seeding quality, the target parameters were optimized for wheat and buckwheat by Design-Expert. According to the operational requirements and response surface analysis, combined with the impact of *LHST* on falling time, the optimal constraint conditions were selected, and the minimum value was obtained with target value of *SUCVR* and *RDS*. Following conditions are needed to be met:

$$\begin{cases} \min C_{v1} \\ \min Y_1 \\ 20 \leq X_1 \leq 31.5 \\ 3.9 \leq X_2 \leq 8.1 \\ 1101 \leq X_3 \leq 1399 \end{cases} \quad \text{or} \quad \begin{cases} \min C_{v2} \\ \min Y_2 \\ 20 \leq X_1 \leq 31.5 \\ 3.9 \leq X_2 \leq 8.1 \\ 711 \leq X_3 \leq 889 \end{cases}$$

It was clear from parameter optimization conditions that the requirements for X_1 and X_2 of wheat and buckwheat were the same, while conditions for X_3 were different. The functional constraints of X_3 were from 1101 to 1399 r/min for wheat and from 711 to 889 r/min for buckwheat. Through fitting results of the orthogonal rotation combination experiment, double-objective optimization was performed. For wheat, optimized results were as follows: *LHST* was 27.19 mm (took 27.2 mm), *RSCCT* was 4.52 r/min (took 4.5 r/min), and *RSSD* was 1169.57 r/min (took the small value of 1169 r/min). In this condition, theoretical values of *SUCVR* and *RDS* of wheat were 5.11% and 0.01%. The optimal combination parameters of buckwheat were solved that the *LHST* was 26.53 mm (took 26.5 mm), *RSCCT* was 3.92 r/min (took 3.9 r/min), and *RSSD* was 711 r/min. Finally, the theoretical *SUCVR* and *RDS* were 4.69% and 0.117% for buckwheat.

Finally, the optimal parameter combination was verified. The experiment was repeated 3 times and average value was taken. The results showed that the average *SUCVR* and *RDS* of wheat were 5.02% and 0.117%, and the average value *SUCVR* and *RDS* of buckwheat were 4.74% and 0.113%, respectively. The experimental results were basically consistent with the theoretical optimization results, which meant that the optimization of operating parameters was credible at the laboratory conditions. Compared with the performance before optimization, the seeding performance has been significantly improved with the optimal parameter combination. These laboratory data suggested an optimized combination of parameter was needed for plot seeding to maximize seeding performance.

4 Conclusions

In order to improve the seeding performance of plot drill, cone compartment tray of seeding device was taken as research object in this paper, and seeding control system was designed. Three experiment factors (*LHST*, *RSCCT* and *RSSD*) and two test indicators (*SUCVR* and *RDS*) were used to investigate the influence of each factor on seeding performance of wheat and buckwheat. The operating parameters were optimized. The specific conclusions of this research were as follows:

(1) The development of seeding control system could enable stepless adjustment of *RSCCT* and *RSSD* in the seeding device. This system used Android terminal as a human-machine interaction interface, STM32 as the control core, brushless DC motor to drive seed distributor, and the stepper motor to drive cone compartment tray to replace ground wheel and chain driven systems.

(2) Base on the designed seeding control system, laboratory experiments were conducted. The results showed that the main factors affecting the changes of *SUCVR* for wheat were *RSSD*, *RSCCT* and *LHST* in order. For buckwheat, the impact of *RSCCT* on *SUCVR* was more important than *RSSD*, which was slightly different from wheat. *RSSD* was main factor affecting damage of wheat and buckwheat. *RDS* increased with the increase of *RSSD*. Therefore, *RSSD* should be reduced as much as possible to reduce the rate of damaged seeds under the condition of meeting uniformity requirements of seeding.

(3) The mathematical model of relationship among *LHST*, *RSCCT* and *RSSD* was established. The operating parameters were optimized. Optimized wheat working parameters were that *LHST* was 27.2 mm, *RSCCT* was 4.5 r/min, and *RSSD* was 1169 r/min. The bench test results showed that *SUCVR* was 5.02% and *RDS* was 0.117%. Under the parameter combination of *LHST* of 26.5 mm, *RSCCT* of 3.9 r/min, and *RSSD* of 711 r/min, buckwheat had good seeding performance, and *SUCVR* and *RDS* values were 4.74% and 0.113% in the laboratory experiments, respectively.

The seeding control system and indoor bench can be used to conduct operating parameter tests for different seeds before sowing in the field. In order to provide a complete mechanical matching relationship between electro-mechanic drive system and plot drill, further studies may be required to determine the relationship of *RSCCT*, length of plot, and walking speed of plot drill.

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