Theoretical and Experimental Studies on Air-suction Roller-type Precision Seed-Metering Device

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Abstract: The seed-metering device is the key component of a precision seeder. The methods to improve the seed suction and dropping efficiency of air suction drum precision seed metering device were discussed. Establishing the force and equation of motion for sucking, carrying and dropping stages, the effect of the seeding parameters on the effect of sucking and seeding is analyzed. Then, the single factor and orthogonal test are carried out on the sucking pressure, the carrying pressure, the rotation rate and the dropping pressure as the experimental factors for the optimization analysis. And the optimum experimental parameters and the predicted values of each test index are obtained. That is, when the seeding pressure of -2.87kPa, the seeding pressure of -1.91kPa, the drum rotation rate of 18.72 r min$^{-1}$ and the dropping pressure of 1.74kPa, the best effect that the single rate is 93.8%.

1. Introduction
With the development of agricultural mechanization, the application of precision sowing has been one of the most significant directions in the facilities agriculture. The largest part of production increase is attributed to the increased utilization of mechanical energy and development of more effective machines and implements. Among the machines contributing to higher yield in current farming are planting machines$^{[1]}$. It has been an important developing direction to improve the efficiency of farming and to realize the plant uniform distribution, the rational close planting. Seeding has been an important problem restricting the development of the seedling industry. According to the working principle, the metering device is the core of precision sowing, which can be divided into the mechanical type, the vacuum type, and the magnetic type seeder$^{[2]}$. The vacuum precision seeder is the application using the negative pressure air flow to suck the seeds from the vibration seeds bed$^{[3]}$. The advantages are following: the better working quality, the more precise seed rates with lower rate of seeds damage, the better control and adjustment, and the broader spectrum of applicability. The forces acting on the seeds during the sucking process are the main factors impacting seeds suction performance. However, the current
performance studies on vacuum precision seeder are still relying largely on the tests. The drum-type metering device in the process is affected by many factors, which are the suction pressure, the carrying pressure, the drum rotation rate and the dropping pressure[4-5]. The parameter selection for metering the suction effect has a lot of influence. Based on the drum-type metering device in the process of working, the study on the effects of suction and discharge lay the foundation for industrialization of drum-type seeder.

This paper selects one representative seeds which is tomato seeds for experiment and builds the mathematical model base on the various factors about the qualified rate, the replay rate and the leakage rate, then optimizing the model of optimal parameter combination [6].

2. Theory and calculation
There were many factors that influence the seeding effect of the air-suction roller-type precision seed metering device, including the structure parameters and the operating parameters of the seed metering device[7]. For estimating the optimum vacuum pressure of a precision vacuum seeder a mathematical model is developed by using physical properties of seeds viz [8]. In this paper, the effect of the seeding parameters on seeding effect is analyzed. The working process of the seeding device could be divided into three stages: the sucking stage, the carrying stage and the dropping stage are as shown in Figure 1.

Fig 1 metering process

For the three stages of stress analysis can be obtained, and the adsorption conditions of the sucking stage are as follows:

\[
\frac{\rho C_d Q^2}{\pi \rho_z d_z R_z^2 (1 - \cos \gamma)^2} \geq G \left( \frac{\cos \alpha}{\tan \varphi_2} - \sin \alpha \right) \tag{1}
\]

Where, G is the gravity on the seed, N; C_d is the dimensionless coefficient, related to the shape of the object, the surface state and the Reynolds number; Q is the gas flow, m³ s⁻¹; α is the angle of the pumping position that when the seed is adsorbed, the angle between the centroid of the seed and the center line of the drum and the horizontal line of the center of the roller, rad; φ₂ is the friction angle between the drum and the seed; p is the density of the air, kg m⁻³; dz is the seed diameter, m; ρ is the density of the air, kg m⁻³; Rz is the suction radius, m; 2γ is the angle near the suction hole cone, rad; g is the gravity acceleration, m s⁻².

The adsorption conditions of the carrying stage are as follows:

\[
\Delta P \frac{\rho d_x^2}{4} \geq m (g \cot \varphi_2 + R_G \omega^2) \tag{2}
\]

Where, ΔP is the suction pore pressure difference, Pa; d_x is the suction pore radius, m; m is the seed quality, kg; R_G is the radius of metering device, m; ω is run rotation rate, rad s⁻¹;

The equation motion of the dropping stage are as follows:
\[
\begin{align*}
V_X &= \int_0^T a_X \, dt, L_X = \int_0^T a_X \, d^2t \\
V_Y &= \omega R_G + \int_0^T a_Y \, dt, L_Y = \omega R_G T + \int_0^T a_Y \, d^2t 
\end{align*}
\]

(3)

Where, \(V_X\) is the X axis speed, \(m \, s^{-1}\); \(V_Y\) is the Y axis speed, \(m \, s^{-1}\); \(a_X\) is the X axis acceleration, \(m^2 \, s^{-1}\); \(a_Y\) is the Y axis acceleration, \(m^2 \, s^{-1}\); \(t\) is the time of seeds from seed, \(s\); \(L_X\) is the seed in the X direction of the displacement, \(m\); \(L_Y\) is the seed in the Y direction of the displacement, \(m\).

2.1. Effects of sucking pressure and carrying pressure

The magnitude of the suction pressure and the carrying pressure determines the air flow rate \(Q\) in the sucking stage and the pressure difference of the suction hole \(\Delta P\) in the carrying stage. It can be drawn from the formula (1.1) that the magnitude of the adsorption force is proportional to the square of the air flow rate \(Q\), and that the increasing of the air flow rate can greatly improve the suction effect; Formula (1.2) shows that the adsorption force is determined by the difference of the suction pressure and external pressure viz \(\Delta P\). Thus, the increasing suction pressure and the carrying pressure will contribute to the sorption of seeds. However, excessive suction pressure will cause a suction hole to absorb extra seeds, which makes it difficult for the seeds to be blown off and make the re-seeding rate is high.

2.2. Effect of drum rotation rate

It can be seen from the formula (1), (2), (3) that the drum rotation rate has a great influence on the carrying stage and the dropping stage. Increasing rotation rate will reduce the contact time of the seed and the suction hole in the sucking stage and the probability of the seeds being adsorbed. The increase of the rotation rate will result in an increase of the adsorption force in the carrying stage, which leads to the increase of sucking and carrying pressure, and also leads to increase the seeding energy consumption; At the same time, it will increase the final speed of the seeds into the plug, thereby increasing the instability of the seeding effect. In addition, it also can be seen that increasing the drum rotation rate will bring about the decline of seeding quality and the increase of planting cost. However, an important way to improve the efficiency of seeding is to increase the drum rotation rate, so the drum rotation rate must be determined by the comprehensive experiments.

2.3. Effect of dropping pressure

Ignoring the air resistance, the seeds leave the suction hole only by the gravity and the jet field force. The jet field is a turbulent jet formed by a positive pressure jet which is ejected from a suction hole. From the theory of hydrodynamics, it can be seen that the velocity of the jet field is the largest and the radial velocity gradually decreases, the axial velocity decreases with increasing distance of the suction hole, regardless of whether the jet field is at the beginning or the main segment. At the same time, after the seeds leaving the suction hole, the suction hole still continue to rotate at a constant speed, the jet field will change with it. It can be seen that the force exerted by the seed from the suction hole is still very complicated. And it is difficult to ensure seamless switching between the positive and negative pressure. The jet field distribution of the suction hole on the same bus is also difficult to ensure exactly the same, and the time that the seeds on the same bus dropping the same distance is inconsistent. Different distance of movement, thereby affecting the seeding effect. In addition, excessive positive seeding pressure will cause the seeds to fall into plug at a higher speed and easily rebound out of the hole, resulting in decrease quality of seeding. Therefore, minimizing the seeding pressure and seed gas flow rate can reduce the influence of turbulent flow field on the seed drop process, and improve the uniformity and stability of seed row effectively.

3. Material and methods

According on the above analysis, the factors that affect the effect of seeding are sucking pressure, carrying pressure, drum rotation rate and dropping pressure. However, these analyses are qualitative,
and the effect of each factor on the effect of seeding is still unknown, and a single factor test is needed to analyze the extent to which the factors affect the test index from a quantitative perspective\[15\].

3.1. Effect of the suction pressure
Set the drum speed of 20 \( r\ \text{min}^{-1}\), the dropping pressure of 2kPa, the carrying pressure of 2kPa. Select the suction pressure -1kPa, -2kPa, -3kPa, -4kPa, -5kPa experiment with five levels, the suction pressure to test indicators in Figure 2 below.

![Figure 2 Effects of Negative Pressure on Test Index](image)

As shown in Figure 2, with the increase of negative pressure, single rate increased first and then decreased, and the maximum value is between 3kPa and 4kPa. The re-seeding rate increase and the missed rate decrease monotonically. Therefore, in order to improve the quality of seeding, the suction negative pressure cannot be too high or too low. If the negative pressure is too low, the seed metering device will not be able to adsorb seeds, resulting in seed missed rate increased; Conversely, the seed metering device will absorb extral seeds, resulting in the re-seeding rate increased.

3.2. Effect of the carrying pressure
Set the drum rotation rate of 20\( r\ \text{min}^{-1}\), the dropping pressure of 2kPa, the suction pressure of -3kPa. The experiments is carried out at the levels of -1kPa, -2kPa, -3kPa, -4kPa and -5kPa. The effect of carrying pressure on the test index is shown in Figure 3.

From Fig3, it can be seen that under the current experimental conditions, with the increase of negative pressure of seed suction, the single seed first increase and then decrease, and there is a maximum between 2 kPa and 3 kPa. The re-seeding rate increase monotonously, while the missed rate decrease monotonously. The negative pressure is mainly affected by the seed-clearing. If the negative pressure is too low, it is easy to be blown away from the drum when the seeding is cleared, resulting in missed rate increased; And if the negative pressure is too high, it will lead to excess seeds can’t be blown off the drum, resulting in the re-seeding rate increased.
3.3. Effect of the drum rotation rate

Set the suction pressure of 3kPa, the carrying pressure of 2kPa, the dropping pressure of 2kPa. The test is carried out at five levels of drum rotation rate of 10r min\(^{-1}\), 20r min\(^{-1}\), 30r min\(^{-1}\), 40r min\(^{-1}\) and 50r min\(^{-1}\). The influence of drum rotation rate on the test index is shown in Figure 4.

It can be seen from Fig4 that the single rate decreases monotonously with the increase of the rotation rate of the drum, mainly because the contact time of the suction hole and seed is longer when the rotation rate is low, and the adsorption effect is better. With the increase of rotation rate, the contact time between the suction hole and the seed becomes shorter and shorter, and the inertial force of the seed increases, the effect of suction and seeding drops rapidly. The seeding rate decreased slightly, and then increased mainly due to the early drum rotation rate increases, the process of shortening, so the seeding rate will be slightly decreased.

With the drum rotation rate increasing, the suction efficiency of the seed is improved. However, from the above analysis, when other factors are certain, the effect of seed suction decreases with the increase of the rotational speed of the drum. Therefore, we need to find a balance between the efficiency and the quality.
3.4 Effect of the dropping pressure

Set the drum rotation rate of 20r min⁻², the suction pressure of 3kPa, the carrying pressure of 2kPa. When the dropping pressure is 1kPa, 2kPa, 3kPa, 4kPa and 5kPa, the effect of seed pressure on the test index is shown in Figure 5.

![Figure 5 The Effects of Negative Pressure on Test Indexes](image)

As shown in the Fig5, with the increase of positive pressure, the single rate increases first and then decreases, and it has the maximum value between 1kPa and 2kPa, and re-seeding rate and missed rate decreases first and then increases. The reason for this phenomenon may be that when the positive pressure is small, the seeds cannot easily fall off from the drum, and some seeds cannot be precisely seeded from the seed position, then the suction hole is blocked; When the seed positive pressure increases, the seeds can fall off smoothly. However, the seed falling process is more and more affected by the positive pressure airflow. When the positive pressure of seeding reaches a certain degree, even the seeds that have fallen into plug will be blown out. Therefore, the correct size of the seed row of positive pressure is particularly important for the effect of suction seeds \[16\].

4. Orthogonal experiment

From the results of single-factor test, it can be known that each factor has different influence on the seeding effect and each factor is interdependent. And the interaction between each factor is very complicated. Single factor experiment is difficult to explore, so it is necessary to carry out the orthogonal test. It is necessary to explore the interaction between the various factors on the effect of seeding, and then get the best combination of parameters. Orthogonal test is an effective test method to deal with multi-factor and multi-level test. It makes the test conditions of all the factors at the same level, with neatly comparable and balanced dispensability, which can reduce the number of tests and obtain better experimental results \[17\]. However, the traditional orthogonal design can only find the optimal parameter combination, but not the optimal parameter solution. Regression Orthogonal design combines the advantages of orthogonal design and regression analysis, not only with reasonable test design and fewer trials, but also to establish an effective mathematical model \[18-19\]. It can choose the appropriate test points within the scope of the factor test, with less test to establish a high precision, good statistical regression equation, and can solve the problem of experimental optimization. Considering the elimination of errors, the introduction of rotating design \[20\]. Therefore, this paper uses the regression orthogonal rotation design experiment to explore the interaction effect of various factors on the effect of sucking seed \[21\].

Regression analysis of the test results using the Design Expert software and the regression model for the three test parameters are shown below.
Single rate of regression model:
\[ y_1 = 91.52 + 0.8x_1 + 1.36x_2 - 2.88x_3 - 4.96x_4 - 1.11x_1x_2 + 0.19x_3x_1 + 0.42x_1x_3 - 1.08x_2x_3 + 1.92x_2x_4 - 1.48x_3x_4 - 5.18x_2^2 - 3.06x_4^2 - 2.67x_3^2 - 3.35x_1^2 \] (4)

Re-seeding rate of regression model:
\[ y_2 = 3.46 + 1.15x_1 + 1.43x_2 - 1.15x_3 - 0.80x_4 + 0.96x_1x_2 + 0.96x_1x_3 - 1.08x_2x_3 + 0.57x_2x_4 + 0.37x_3x_1 - 0.36x_3x_4 + 1.28x_4^2 + 1.20x_4^2 + 0.53x_4^2 + 1.31x_4^2 \] (5)

Missed rates of regression model:
\[ y_3 = 5.03 - 1.94x_1 - 2.79x_2 + 4.03x_3 + 5.77x_4 + 0.15x_1x_2 - 1.15x_1x_4 + 0.66x_2x_3 + 1.65x_2x_4 - 2.29x_3x_4 + 1.84x_3x_4 + 3.91x_1^2 + 1.86x_2^2 + 2.15x_3^2 + 2.03x_4^2 \] (6)

From the above analysis, it can be seen that the increase of drum rotation rate will lead to the improvement of suction efficiency and the decrease of suction quality. In order to determine the optimal matching parameters, it is necessary to further study the interactive effects of various factors on the effect of sorption. Response surface analysis is used to analyze the relationship between each factor by using the response surface function in Design Expert, so as to obtain the interaction relationship among the factors\(^{[22]}\). In the design of the seed metering device, the single rate, the re-seeding rate, the rate of missing sowing and the increase of single rate are the most important factors. Therefore, further analysis is as follows.

4.1. The effect of the interaction between suction pressure and carrying pressure on the single rate

Figure 6 shows the response curve of the suction pressure-carrying pressure to single rate under the conditions of drum rotation rate of 20r min\(^{-1}\) and dropping pressure of 2kPa. It can be seen from the figure, the suction pressure and the carrying pressure on the impact of a single rate is a significant non-linear relationship. When the suction pressure and carrying pressure increased, the single rate increases first and then decreases. When one of the two pressures increases and the other decreases, the change rate of single rate is smaller than that of both increasing and decreasing at the same time. It can be seen from Figure 6 that the variation gradient of single rate is greater in the direction of the suction pressure than in the direction of the carrying pressure, indicating that the effect of suction pressure on single rate is higher than that of carrying pressure. When the suction pressure is in -2.5 ~ -3.5kPa and carrying pressure is in the -1.7 ~ -2.5kPa, the single rate is higher. The maximum value of the single rate is 92.3% when the suction pressure is -3.06kPa and the carrying pressure is -2.12kPa.
Figure 6 Single rate of suction pressure - carrying pressure response surface map

4.2. The effect of interaction between suction pressure and rotation rate on single rate

Figure 7 shows the response curve of the suction pressure - dropping speed to single rate when the carrying pressure is -2kPa and the dropping pressure is 2kPa. In the figure, it can be seen that the single rate is higher in the low speed of drum rotation; When the drum rotation rate is higher, the single rate changes rapidly with the change of the suction pressure. When the suction pressure is -2.5 ~ -3.5kPa and the drum rotation rate is 15 ~ 21r min\(^{-1}\), the single rate is higher. When the suction pressure is -3.08kPa and the drum rotation rate is 16.67r min\(^{-1}\), the single rate reaches the maximum value, which is 92.8%.
Figure 7 Single rate of suction pressure – drum rotation rate response surface
4.3. The effect of interaction between carrying pressure and drum rotation rate on single size

Figure 8 shows the response surface of single rate of carrying pressure - drum rotation rate when suction pressure is -3kPa and dropping pressure is 2kPa. It can be seen that the change trend of single rate is similar to that of figure 7. When the rotational speed of the drum is low, the single rate is high; When the drum rotational speed is high, the single rate changes rapidly with the change of the carrying pressure. When the carrying pressure is -1.5 ~ -2.4kPa and the drum speed is 15~19r min\(^{-1}\), the single rate is higher. When the seed pressure is -2.13kPa and the drum rotation rate is 16.72 r min\(^{-1}\), the single rate appeared the maximum, which is 92.9%.

Figure 8 Single rate of carrying pressure-drum rotation rate response surface
4.4. Optimized combination of parameters

Based on the analysis of the influence of the above factors on the single rate, the suitable parameters of each factor are as follows: the suction pressure is -2.5 ~ -3.5 kPa, the carrying pressure is -1.5 ~ -2.4 kPa, the drum rotation rate is 15 ~ 19 r min⁻¹, the dropping pressure is 1.5 ~ 2.1 kPa. The optimal combination of parameters is shown in Table 1 using the Design Expert optimization function [23-24].

| Suction pressure(-kPa) | Carrying pressure(-kPa) | Drum rotation rate(r min⁻¹) | Dropping pressure(kPa) | Single rate(%) | Re-seeding rate(%) | Missed rate(%) | Reliability(%) |
|------------------------|-------------------------|-----------------------------|------------------------|---------------|-------------------|---------------|--------------|
| 2.87                   | 1.91                    | 18.72                       | 1.74                   | 93.8          | 2.8               | 3.4           | 0.828        |

5. Conclusion

In this paper, tomato seeds are used to explore the method of improving the precision of Seed-Metering Device. Firstly, the single factor experiment is carried out to analyze the influence of various factors on the effect of seeding, and then orthogonal test is carried out to get the best matching parameter of the seeding process.

1) From the theoretical analysis, we can see that the sucking pressure, the carrying pressure, the drum rotation rate and the dropping pressure have a great impact on seeding.

2) When the sucking pressure and the carrying pressure increase, the single rate firstly increases and then decreases. When one of the two pressures (sucking pressure and carrying pressure) increases and the other decreases, the change rate of single rate is smaller than that of both increasing and decreasing at the same time. The effect of suction pressure on single rate is bigger than the carrying pressure. When the suction pressure is -3.06 kPa and the carrying pressure is -2.12 kPa, the single rate reached a maximum value of 92.3%.

3) When the drum rotation rate is low, single rate is higher; When the drum rotation rate is high, the single rate with the suction pressure changes rapidly. The single rate reach 92.8% when the suction pressure is -3.08 kPa and drum rotation rate is 16.67 r min⁻¹.

4) The effect of carrying pressure-drum rotation rate on single rate is similar to that of suction pressure – drum rotation rate on single rate. When the carrying pressure is at a high level and the drum rotation rate is at a low level, the single rate is higher. When the carrying pressure is -2.13 kPa and drum rotation rate is 16.72 r min⁻¹, the single rate reaches 92.9%.

5) The optimized parameters are as follows: when the suction pressure is -2.87 kPa, the carrying pressure is -1.9 kPa, the drum rotation rate is 18.72 r min⁻¹ and the dropping pressure is 1.74 kPa, the single rate is 93.8%, the re-seeding rate is 2.8%, missed rate is 3.4%.

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