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THE INFLUENCE OF SEED VARIETY AND HIGH SEEDING SPEED ON PNEUMATIC PRECISION SEED METERING

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KEYWORDS

corn, seed meter device, high-speed seeding, precision seeding, experiment.

ABSTRACT

Pneumatic seed metering devices are widely used in high-speed and precise corn seeding operations. The objective of this study was to analysis the high-speed seeding performance of a pneumatic precision seed metering device at seeding speed ≥12 km/h. In this study, full-factor experiments were conducted of an air-suction rotary-hub corn precision seed metering device at the early stage of development. Seed leaking was the primary failure mode, and the experimental factors had no evident regular influence on the repeat index. The negative pressure of 3-7 kPa had significantly positive and negative correlations with the qualified index and the leak index, whereas the seeding speed of 12-20 km/h was significantly negatively and positively correlated with the qualified index and the leak index, respectively. The leak index reached its greatest value of 32.48%, 15.61% and 66.77% when the negative pressure was 3 kPa, and it was always less than 10% when the negative pressure was greater than 6 kPa for the three corn seed varieties. The corn seed varieties with smaller sizes and regular shapes were more suitable for high-speed precision seeding operations above 12 km/h, and the negative pressure could be increased to improve the qualified index and reduce the leak index.

INTRODUCTION

Corn is one of the three major staple crops in China and is mainly cultivated in north China (Yao et al., 2022; Liu et al., 2021; Li et al., 2021a), such as the Northeast Black Soil Region and the Huang-Huai-Hai Plain (Xu et al., 2019). In corn sowing operations, precision seeding technology has been proven to save seeds, reduce labour costs and improve crop yields (Li et al., 2015; Yazgi & Degirmencioglu, 2007; Liao et al., 2006), which has become a meaningful way to promote corn's sustainable development. The precision seed meter is the core component for realizing precision mechanized corn seeding. According to the working principle, it can be divided into mechanical and pneumatic types (Fu et al., 2018). Due to the problems of low seeding speed (≤ 6 km/h), strict requirements on seed characteristics and high single-seed rate, mechanical precision seed metering devices are gradually being replaced by pneumatic seed metering devices in agricultural production (Yang et al., 2016; Woo et al., 2017). Pneumatic seed metering devices mainly include types of air blowing, air suction and air pressure (Zhao & Hu, 2012). Because of the advantages of high-accuracy, strong seed adaptability and high operation speed (Zahra & Abdanan, 2018), air suction seed metering devices are increasingly widely used in production.

Currently, much domestic and international research has been carried out on the air suction seed metering device. Yan et al. (2017) developed a pneumatic maize precision seed-metering device with a synchronous rotating seed plate and vacuum chamber, and the bench test showed that the qualified index exceeded 91.6%, the leak index and repeat index were below 5.2% and 5.4% respectively, when the operation velocity was less than 10 km/h and the negative pressure ranged from 3.5 to 5.5 kPa. Yang et al. (2012) designed an air-suction corn precision metering device with a mechanical supporting plate to assist in carrying seeds, and the qualified index was ≥ 91.40%, repeat index ≤ 3.82% and leak index ≤ 4.78% under a seeding speed of ≤ 12 km/h,

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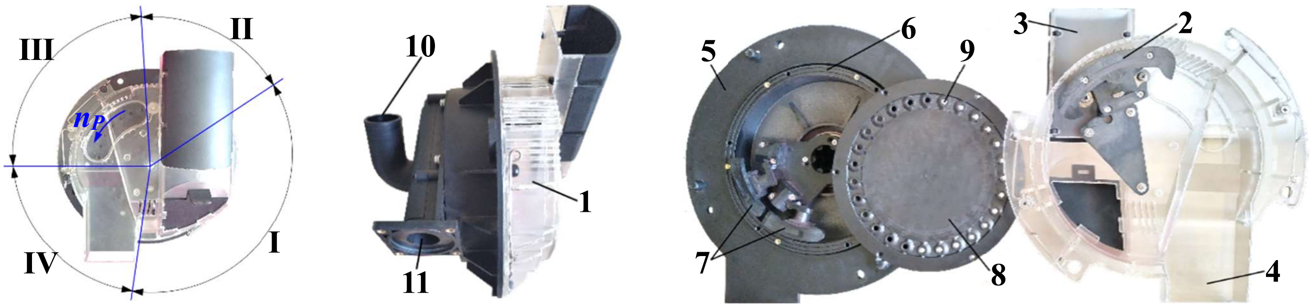
which presented a better seeding effect than a conventional air-suction seed metering device. Liu et al. (2022) optimized the disturbance-assisted seed filling vacuum seed-metering device by DEM-CFD simulation, and the optimization results showed that when the negative pressure was 4 kPa and the working speeds were 8-14 km/h, the qualified index was not less than 95%, and the seed filling performance was relatively stable. Hu et al. (2021) studied the influence law of the suction hole diameter, forward speed and vacuum degree on seeding performance by the Box-Behnken rotation-orthogonal combination experiment. Karayel et al. (2004) established a mathematical model between the negative pressure of the air-suction seed meter and the physical characteristics of crop seeds, and determined the optimal working negative pressure for different crop seeds through experiments at a seeding speed of 3.6 km/h. Bereket (2004) studied the effect of the vacuum pressure, the seed suction hole and thousand-grain weight on corn seeding at 0.16-0.40 m s^{-1} peripheral velocities of seed plate, which found that the most suitable shape of seed suction hole was oblong for maize seeds.

Due to the decreasing agricultural labour power, China's demand for high-speed precision sowing of corn is growing. Existing studies mainly focus on the design and parameter optimization of the pneumatic seed metering device under a seeding speed of less than 12 km/h, and there are few studies focusing on high-speed operating performance. Therefore, an experimental study on corn precision seed metering at high seeding speed of 12-20 km/h was conducted, based on the air-suction rotary-hub corn precision seed metering device developed and applied in batches in Northeast China, which is suitable for high-speed corn seeding, with the goal of providing technical support for stable and reliable high-speed precise corn sowing in the field. For this purpose, rotational speed and negative pressure were selected as the experimental factors to carry out two-factor and five-level full-factor experiments under three different corn seed varieties. Finally, the three indicators of the qualified index, leak broadcast index and repeat index were measured, and the significance analysis of the experiment results was performed.

MATERIAL AND METHODS

Structure and Working Principle of the Seed Metering Device

The overall structure and working principle of the air-suction rotary-hub corn precision seed metering device are shown in Figure 1, which is mainly composed of a front shield, outer shell, discharge plate, inner rotating shell, seed-cleaning device, seed-unloading device, airway and gearing. The discharge plate was tightly connected to the inner rotating shell to form a negative pressure chamber, and the negative pressure chamber and the outer shell were combined to form a rotating connection. The seed-unloading device and the seed-cleaning device were arranged inside and outside the negative pressure chamber, respectively.



(a) Working principle (b) Overall structure (c) Internal structure

FIGURE 1. Structure and working principle of the air-suction rotary-hub corn precision seed metering device.

Note: 1. Front shield 2. Seed-cleaning device 3. Seed inlet 4. Seed outlet 5. Outer shell 6. Inner rotating shell 7. Seed-unloading device 8. Discharge plate 9. Seed suction hole 10. Airway 11. Gearing. I is the seed-filling zone. II is the seed-cleaning zone; III is the seed-transporting zone; IV is the seed-unloading zone; n_P is the rotational speed of the seed-metering device.

During seed metering, negative pressure airflow enters the negative pressure chamber through the airway. Corn seeds enter from the seed inlet on the upper part of the front shield and are adsorbed on the seed suction holes of the discharge plate under the action of negative pressure in the seed-filling zone I. The rotation of the negative pressure chamber is driven by gearing. Excess seeds are removed, by the action of the seed-cleaning device in the seed-cleaning zone II, to ensure that a single seed adsorbed by a single seed suction hole is transported to the seed-unloading zone IV. In the seed-unloading zone IV, the negative pressure airflow of the seed suction hole is blocked, and then the seed is discharged from the seed outlet of the front shield under the action of gravity.

Experimental Platform for Seed Metering

The seed metering experimental platform comprises a rack, seed box, seed spout, motor, electric fan, intelligent control terminal, high-speed camera, and air-suction rotary-hub corn precision seed metering device, as shown in Figure 2. The electric energy of the seed metering experimental platform was supplied by direct-current power. The operation parameter adjustment of the air-suction rotary-hub corn precision seed metering device was realized by an intelligent control terminal controlling the motor and electric fan. The high-speed camera recorded the passage of seeds from the seed-cleaning zone to the seed-unloading zone in order to count the seed suction of the seed metering device. With an acquisition cycle of 1 ms and an exposure time of 0.5 ms, the high-speed camera was set to capture by frame and parallel exposure.

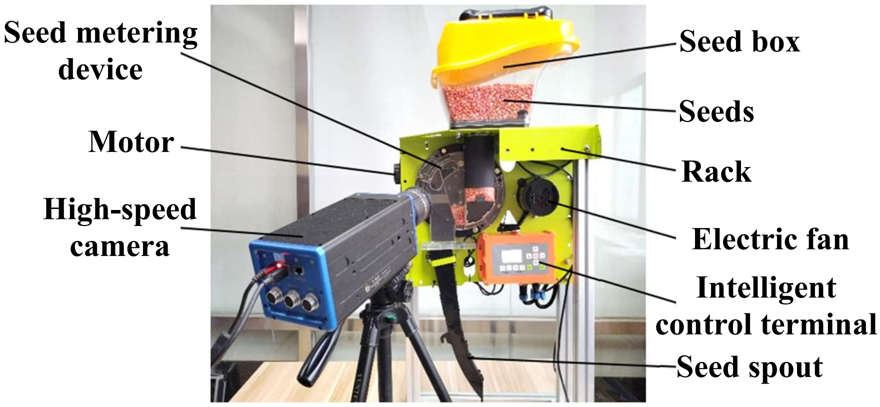
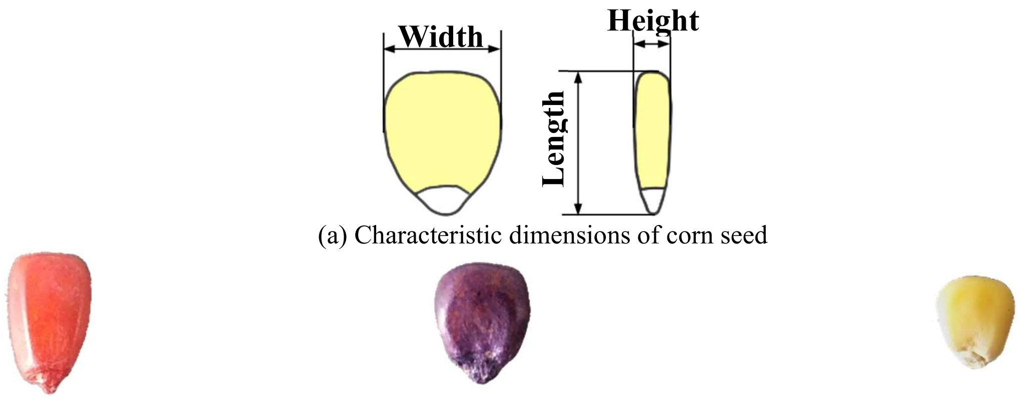


FIGURE 2. Platform for high speed precision metering.

Experimental materials

The geometric features of corn seeds are crucial to the performance experiment and analysis of the seed metering device. Three varieties of corn seeds, NK 718, Xianyu 335 and Heinuo 301, were selected to carry out high-speed precision seed metering experiments. These three kinds of corn seeds are widely planted in China, with obvious geometrical differences. Among them, NK 718 is a slender horseshoe-shaped large grain, Xianyu 335 is a relatively broad and thick irregular spherical medium grain, while Heinuo 301 is a small flat kernel. Three different varieties of corn seeds are shown in Figure 3.



(a) Characteristic dimensions of corn seed

(b) NK 718 (c) Xianyu 335 (d) Heinuo 301

FIGURE 3. Three varieties of corn seeds.

There were considerable differences in the geometric dimensions between different corn seed varieties, as shown in Table 1. To facilitate the experimental research, corn seeds were classified and screened within the same variety.

TABLE 1. Geometric dimensions of the three different varieties of corn seeds.

Seed variety	Parameters	Average value(mm)	Maximum value(mm)	Minimum value(mm)	Standard deviation
NK 718	Length	13.8	16.4	13.1	0.94
	Width	8.0	8.3	7.7	0.24
	Height	4.9	5.8	4.0	0.56
Xianyu 335	Length	10.6	11.6	9.4	0.66
	Width	9.2	9.6	8.2	0.39
	Height	6.2	6.8	5.5	0.50
Heinuo 301	Length	8.8	10.2	7.7	0.75
	Width	8.2	8.9	7.4	0.60
	Height	4.8	5.7	4.2	0.44

Experimental design

In order to study the high-speed operation performance of the air-suction rotary-hub corn precision seed metering device, two-factor and five-level full-factor experiments were carried out under three different corn seed varieties. Based on preliminary experimental research and combined with the research results of relevant scholars (Gao et al., 2019; Yang et al., 2019; Ding et al., 2018;), the negative pressure (P_F), the rotational speed (n_P) of the seed metering device and the corn seed varieties were selected as experimental factors. The air-suction rotary-hub corn precision seed metering device was designed to achieve high-speed precision seed metering operations at a seeding speed of more than 12 km/h. The equation of rotational speed (Yang et al., 2019) is as follows:

$$n_P = \frac{60\times 100v}{3.6N_K L_Z} \tag{1}$$

in which:

v is the seeding speed of seeder, r/min;

N_K is the number of seed suction holes on the discharge plate,

L_Z is the corn plant spacing, cm.

The number of seed suction holes for the air-suction rotary-hub corn precision seed metering device is 27, and the corn plant spacing is 20 cm according to agronomic requirements. Five levels of rotational speed 37.03 r/min, 43.20 r/min, 49.38 r/min, 55.55 r/min and 61.72 r/min were obtained according to equation (1), under the high seeding speed range of the seeder (12 km/h, 14 km/h, 16 km/h, 18 km/h and 20 km/h, respectively). According to the practical electric fan operating parameters, the negative pressure consisted of five levels: 3 kPa, 4 kPa, 5 kPa, 6 kPa, 7 kPa and 8 kPa. The corn seed varieties were NK 718, Xianyu 335 and Heinuo 301.

Referring to the China National Standard GB/T 6973-2005 "Testing methods of single seeding drills (precision drills)", the qualified index, the leak index and the reply index were calculated as the experimental index. There were 75 experimental groups of the full-factor experiments; each group was repeated three times, and each experiment lasted 1 min. The average value of the three experiments was taken as the test result. The experimental indexes (Gao et al., 2021; Liu et al., 2010a) were calculated as follows:

$$\begin{cases} \delta_1 = \dfrac{N_D}{N_Z} \\ \delta_2 = \dfrac{N_L}{N_Z} \\ \delta_3 = \dfrac{N_C}{N_Z} \end{cases} \tag{2}$$

in which:

δ_1 is the qualified index, %;

δ_2 is the leak index, %;

δ_3 is the repeat index, %;

N_D is the number of single seed metering;

N_Z is the theoretical seed metering quantity;

N_L is the number of seeds not sucked up through the seed suction hole,

N_C is the number of times that the seed suction hole adsorbs multiple seeds.

Data analysis

Microsoft Excel 2016 and SPSS 25.0 were employed to record and analyze experimental data.

RESULTS AND DISCUSSION

The experimental results of the air-suction rotary-hub corn precision seed metering device are shown in Table 2. Overall, the qualified index and leak index of different corn seed varieties showed a decreased and increased trend, respectively, with the increase of the rotational speed, under the same negative pressure. The reason was that the centrifugal force on corn seeds increased with higher rotational speed. The seed leaking occurred because the centrifugal force was higher than the seed suction force (Liu et al., 2010b). In contrast, the qualified index and leak index presented an increased and decreased trend, respectively, with negative pressure increasing under the same rotational speed. Because the increase of negative pressure enhanced the seed suction force (Yang et al., 2019; Karayel et al., 2004), the corn seeds were more tightly adsorbed on the discharge plate. Furthermore, the seed repeat phenomenon rarely occurred under high-speed operation, and the experimental factors had no evident regular influence on the repeat index. Therefore, seed leaking was the primary failure mode of the air-suction rotary-hub corn precision seed metering device in the high-speed precision seed metering operation, and the negative pressure can be increased to improve the qualified index and reduce the leak index during the high-speed process.

TABLE 2. Experiment combination and results.

No.	P_F (kPa)	n_P (r/min)	δ_1 (%)			δ_2 (%)			δ_3 (%)		
			NK 318	Xianyu 335	Heinuo 301	NK 318	Xianyu 335	Heinuo 301	NK 318	Xianyu 335	Heinuo 301
1	3.0	37.03	84.00	47.29	93.90	16.00	52.71	6.10	0	0	0
2		43.20	84.48	45.22	87.74	15.52	54.78	12.26	0	0	0
3		49.38	62.65	30.70	83.80	37.35	69.30	16.20	0	0	0
4		55.55	56.26	27.79	81.00	43.74	72.21	19.00	0	0	0
5		61.72	50.19	15.15	75.52	49.81	84.85	24.48	0	0	0
6	4.0	37.03	95.70	81.40	99.47	4.30	18.60	0.40	0	0	0.13
7		43.20	92.88	71.36	98.17	7.12	28.64	1.80	0	0	0.03
8		49.38	87.70	60.40	94.07	12.30	39.60	5.93	0	0	0
9		55.55	86.73	53.00	94.60	13.27	47.00	5.40	0	0	0
10		61.72	86.20	41.01	95.20	13.80	58.99	4.80	0	0	0
11	5.0	37.03	99.80	93.20	99.90	0.20	6.80	0	0	0	0.10
12		43.20	98.48	81.05	99.65	1.46	18.95	0.26	0.06	0	0.09
13		49.38	98.42	73.75	99.40	1.58	26.25	0.60	0	0	0
14		55.55	92.00	72.20	98.53	8.00	27.80	1.47	0	0	0
15		61.72	91.66	61.59	98.08	8.34	38.41	1.92	0	0	0
16	6.0	37.03	100	97.70	99.80	0	2.30	0.20	0	0	0
17		43.20	99.49	94.26	99.83	0.51	5.74	0.17	0	0	0
18		49.38	99.85	90.40	100	0.15	9.60	0	0	0	0
19		55.55	97.27	85.00	99.67	2.73	15.00	0.33	0	0	0
20		61.72	95.38	85.42	99.64	4.62	14.58	0.36	0	0	0
21	7.0	37.03	99.90	99.20	99.84	0	0.80	0	0.10	0	0.16
22		43.20	100	98.54	100	0	1.46	0	0	0	0
23		49.38	99.85	96.40	100	0.15	3.60	0	0	0	0
24		55.55	99.27	95.60	100	0.73	4.40	0	0	0	0
25		61.72	99.28	93.46	99.64	0.72	6.54	0.36	0	0	0

The significance analysis of experimental results was conducted to clarify further the effects of rotational speed and negative pressure on the qualified index and leak index. Under the same corn seed variety, the significant differences between different rotational speeds and between other negative pressures were indicated by different letters. The significance analysis results are shown in Figure 4 and Figure 5, respectively.

Influence of Experimental Factors on Qualified Index

For NK 718, both negative pressure and rotational speed significantly affected the qualified index. With the increase of negative pressure, the qualified index increased significantly. When the negative pressure was 3 kPa, the minimum qualified index was 67.52%, while the maximum value was 99.66% as the negative pressure was 7 kPa. However, when the negative pressure changes within the range of 5-7 kPa, the qualification index was more than 95%, and there was no significant difference between them. With increasing rotational speed, the qualified index decreased significantly. When the rotational speed was 37.03 r/min, the qualified index was 95.88% of the maximum value, and the qualified index was the minimum value of 84.54% under the rotational speed of 61.72 r/min. If the rotational speed varied within the range of 37.03-49.38 r/min, there was no significant difference between the qualified index, but the qualified index was less than 90% as rotational speed > 49.38 r/min.

For Heinuo 301, negative pressure and rotational speed significantly affected the qualified index. With the increase of negative pressure, the qualified index increased significantly. The qualified index reached the minimum value of 67.52% as the negative pressure was 3 kPa, while the maximum value was 99.90% under the 7 kPa negative pressure. The qualified index decreased significantly with rotational speed growing. The qualified index had a maximum value of 98.58% when the rotational speed was 37.03 r/min, and the minimum value was 93.62% when the rotational speed was 61.72 r/min. In addition, in the range of negative pressure of 4-7 kPa or rotational speed of 37.03-49.38 r/min, the qualified indexes were all >95%, and there was no significant difference between them.

For Xianyu 335, both negative pressure and rotational speed had a significant effect on the qualified index. With the increase of negative pressure, the qualified index increased significantly. The qualified index acquired the minimum value of 33.23% when the negative pressure was 3 kPa, and the maximum value was 99.64% with the 7 kPa negative pressure. There was a significant difference between the qualified index while the negative pressure was 3-6 kPa, and the qualified index was > 95% only when the negative pressure was 7 kPa. The qualified indices were all less than 85% and decreased significantly with the increase in the rotational speed. When the rotational speed was 37.03 r/min, the qualified index reached a maximum value of 83.76%; when the rotational speed was 61.72 r/min, the minimum value of the qualified index was 59.33%.

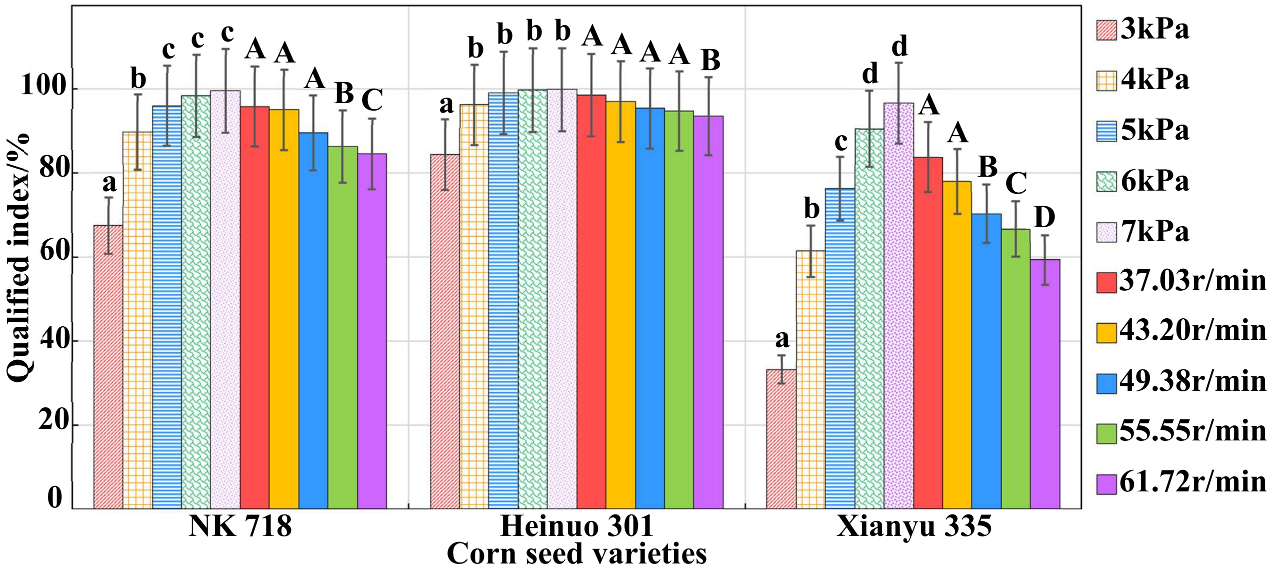


FIGURE 4. Influence of experimental factors on qualified index for different corn seed varieties.

In summary, negative pressure and rotational speed under different corn seed varieties presented positive and negative correlations with the qualified index. Meanwhile, the significant influence of negative pressure and rotational speed on the qualified index differed for different corn seed varieties. Overall, the qualified index of Heinuo 301 under each experimental factor changed relatively smoothly, and the qualified index was relatively the highest. In contrast, the qualified index of Xianyu 335 fluctuated wildly, and the qualified index was relatively low under experimental factors. Further analysis showed that the flat small-grained corn seeds (Heinuo301) and the slender medium-grained maize seeds (NK 718) were more adaptable to high-speed precision seeding operations. In contrast, the relatively generous irregular spherical maize seeds (Xianyu 335) had poor adaptability for high-speed precision seeding. Therefore, corn seed varieties with smaller sizes and regular shapes were more suitable for practical high-speed precision seeding operations ≥ 12 km/h. Corn seeds could also be screened prior to high-speed sowing.

Influence of Experimental Factors on Leak Index

For NK718, both negative pressure and rotational speed significantly affected the leak index. With the increase of negative pressure, the leakage index decreased significantly. However, the effect of negative pressure on the leakage index was not significant when the negative pressure varied from 4 to 6 kPa. When the negative pressure was 3 kPa and 7 kPa, the leak index reached the maximum value of 32.48% and the minimum value of 0.32%, respectively. Although the leak index increased significantly with increasing rotational speed, the effect of rotational speeds of 49.38-61.72 r/min on the leak index was not significant. The leak index acquired a minimum value of 4.10% and a maximum value of 15.46%, as the rotational speed was 37.03 r/min and 61.72 r/min, respectively.

For Heinuo 301, negative pressure and rotational speed significantly affected the leak index. With the increase of negative pressure, the leak index decreased significantly. The leak index achieved a maximum value of 15.61% and a minimum value of 0.07% under negative pressure of 3 kPa and 7 kPa, respectively. With the increase in rotational speed, the leakage index rose significantly. When the rotational speed was 37.03 r/min and 61.72 r/min, the leak index reached a minimum value of 1.34% and the maximum value of 6.38%. In addition, in the range of negative pressure of 4-7 kPa or rotational speed of 43.20-61.72 r/min, there was no significant difference between the leak index, and all were less than 5%.

For Xianyu 335, both negative pressure and rotational speed had a significant effect on the leak index. With the increase of negative pressure, the leak index decreased significantly. The leak index's maximum and minimum values were 66.77% and 3.36%, as the negative pressure was 3 kPa and 7 kPa, respectively. With the increase in rotational speed, the leak index increased significantly. When the rotational speed was 37.03 r/min and 61.72 r/min, the leakage index gained a minimum value of 16.24% and a maximum value of 40.67%. In addition, while the negative pressure was 3-6 kPa or the rotational speed was 37.03-55.55 r/min, there was a significant difference between the leak index and only when the negative pressure was >6 kPa, the leak index was <10%.

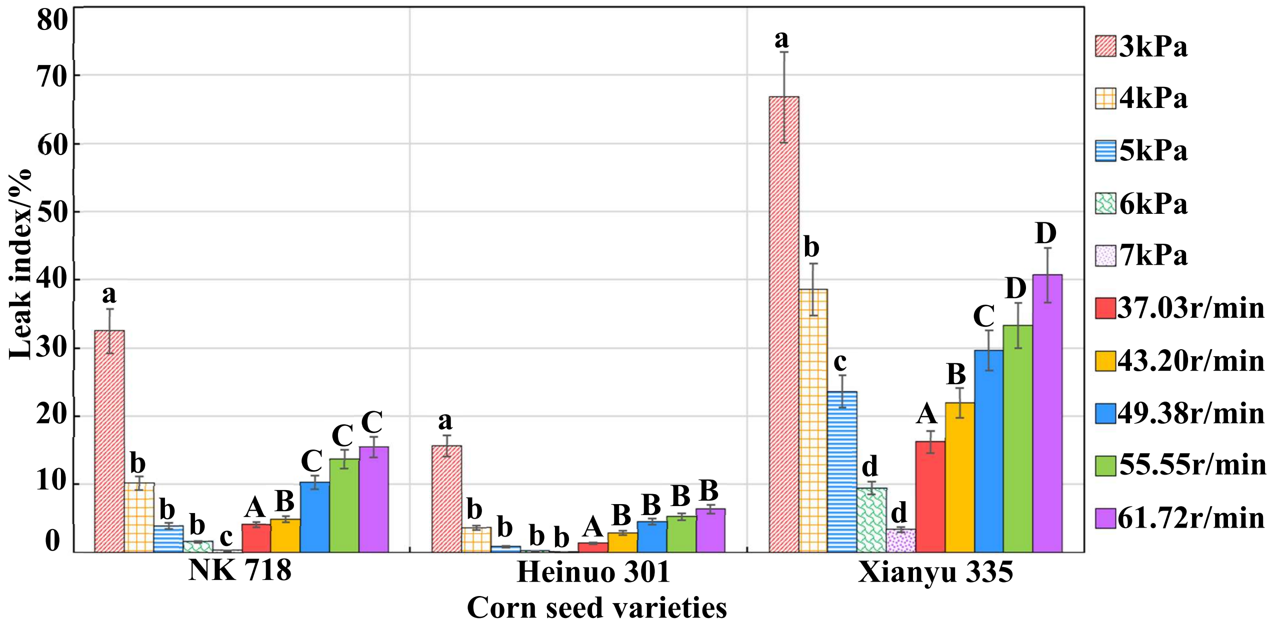


FIGURE 5. Influence of experimental factors on leak index for different corn seed varieties.

In summary, negative pressure was negatively correlated with the leak index under different maize varieties, while rotational speed was positively correlated with the leak index. Meanwhile, the significant influence of negative pressure and rotational speed on the leak index differed for different corn seed varieties. On the whole, Heinuo 301 had a relatively minimal leak index level under various experimental factors, while Xianyu 335 had the maximum leak index. For each corn seed variety, the leak index reached the maximum value under the negative pressure 3 kPa, and it was less than 10% when the negative pressure was greater than 6 kPa. The reason was that the more regular the shape of corn seeds, the easier it was to closely fit them with the seed suction holes, which enhanced the adsorption force of the negative pressure on the corn seeds at the seed suction holes (Han et al., 2018; Zhou et al., 2020; Li et al., 2021b) and further reduced the phenomenon of leak sowing induced by the centrifugal force of the discharge plate and collision between grains. Therefore, the leak index could be reduced by increasing the negative pressure to above 6 kPa according to the characteristics and parameters of corn seeds for high-speed precision seeding operation above 12 km/h.

CONCLUSIONS

(1) In this study, the full-factor experiments of an air-suction rotary-hub corn precision seed metering device were performed. During the high-speed (12-20 km/h) precision seed metering operation, seed leaking was the primary failure mode, and the negative pressure could be increased to improve the qualified index and reduce the leak index. Furthermore, the experimental factors had no evident regular influence on the repeat index for high-speed metering operation.

(2) For the different corn seed varieties, the negative pressure of 3-7 kPa presented significantly positive and negative correlations with the qualified index and the leak index, while the rotational speed of 37.03-61.72 r/min was significantly negatively and positively correlated with the qualified index and the leak index, respectively. Heinuo 301 had a relatively minimal leak index level under various experimental factors, while Xianyu 335 had the fairly maximum leak index.

(3) The significant influence of negative pressure and rotational speed on the qualified index and leak index differed for different corn seed varieties. The leak index reached its greatest value of 32.48%, 15.61% and 66.77% when the negative pressure was 3 kPa, and it was always less than 10% when the negative pressure was greater than 6 kPa for all three corn seed varieties. The corn seed varieties with smaller sizes and regular shapes were more suitable for high-speed precision seeding operations at ≥ 12 km/h, while the relatively generous irregular spherical maize seeds had poor adaptability for high-speed precision seeding.

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