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Research Article

Air Suction Seed-metering Device for Cyperus Esculentus Planting

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Abstract: In order to realize the mechanized planting of cyperus esculentus, reduce its labor input and meet precision sowing requirement, a precision air suction cyperus esculentus seed-metering device was to be developed. Physical characteristics of the cyperus esculentus seeds was to be calculated and analyed. Through calculation and test, diameter of seed discharge plate, numbers of seed suction opening and shape and diameter of the seed suction opening was determined. It designs a mixing device installed on the discharge plate, through the orthogonal experiment it gets the best geometric dimensioning of the mixing device: height is 5 mm and breadth is 3 mm. Through comparison testing that whether there is the mixing device or not on the discharge plate, it determines that the mixing device with the discharge plate has the best seeding performance when the seed suction opening diameter is 6.5 mm.

Keywords: Air suction, cyperus esculentus, orthogonal experiment, physical characteristics, seed-metering device

INTRODUCTION

Cyperus esculentus is also called yellow nutsedge, chufa sedge, earth almond, nut grass (Zhang, 2004). Each cyperus esculentus has 50-250 tubers averagely and each of them weighs about 2-2.6 g. There are about 1000-1300 tubers/kg. Average per mu yield of fresh fruits is above 800 kg and the maximum 2000 kg in top production areas. Dry cyperus esculentus yield is about 600-800 kg, which can produce cooking oil 200-300 kg. Its yield per mu is far above that of soybean, rapeseed and peanut. The cyperus esculentus oil yield is 32-39%, four times as large as that of rapeseed, twice as large as that of peanut. Cyperus esculentus ranks the top output in present economic oil crops, which deserves the title “King of Oil Plants”. As the new type of nutrition and health care cooking oil, clean tawny and mellow, it rivals olive oil. It contains rich linoleic acid and protein, amino acid of high nutritional value, minerals especially kalium and phosphorus. Cyperus esculentus oil has low sodium and zero copeningsterol, being capable to prevent from cardiovascular cerebrovascular diseases and hyperlipidemia. It has fine quality, being far better than rap oil and soybean oil (Chen *et al*., 2008).

Although it is largely demanded in the market, cyperus esculentus has not realized industrialized production and there are seldom seeding devices. People constantly pay attention to the seeder and other mechanical problems. Currently cyperus esculentus generally adopts improved mechanical peanut seeder, which takes mechanical external force seed-metering device. It has great seeding pulsation, poor evenness and high seeds breakage rate. Consequently it is difficult for precision and semi-precision sowing.

In this study it designs an air suction precision seed-metering device for cyperus esculentus planting. It makes optimization design for structure parameter (diameter of the discharge plate, numbers shape and diameter of seed suction opening) of the seed-metering device.

ANALYSIS AND CALCULATION OF PHYSICAL CHARACTERISTICS OF THE CYPERUS ESCULENTUS SEEDS

Seeds physical characteristics are basic to design the seed-metering device. Before the design, firstly it shall determine geometric dimensioning and shape, thousand-seed weight and friction angle of cyperus esculentus seeds.

Geometric dimensioning and shape: Geometric dimensioning and shape refer to seeds length, breadth and depth, being prominent to determine the seed suction opening diameter of the air suction seed-metering device.

Determination method: It randomly chooses 100 seeds, getting length, breadth and depth of each seed by

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Table 1: Measurement weight record

Groups number	1	2	3	4	5	6	7	8
Weight (g)	85	89	80	86	84	86	81	82

vernier caliper. According to the statistics, the average length l is 16.52 mm, average breadth b is 9.80 mm and average depth d is 13.56 mm.

Thousand-seed weight: Thousand-seed weight refers to the weight of 1000 seeds according to the specified moisture. It plays a remarkable role in the calculation of wind pressure in the air suction seed-metering device.

Measurement method: It adopts 100-seed method.

Sampling: It fully mixes all pure seeds after the purity analysis and puts them on the clean desktop. It randomly selects 100 seeds as one group by quartering (to avoid artificial discard). As counting, it puts each five seeds in one pile, combining two piles to get a pile of ten seeds, taking ten piles to get 100 seeds, eight groups in total.

Weighting: It weighs counted samples and enters them in Table 1, the measurement record of thousand-seed weight.

Calculation: According to eight repeating weight readings, it calculates the average weight of eight groups ($\bar{X}$) by the following formula, then calculates standard deviation (S) and coefficient of variation (C).
Standard deviation:

$$S = \sqrt{\frac{n(\sum X^2) - (\sum X)^2}{n(n-1)}} \tag{1}$$

In the formula: X refers to the weight (g) of each repeating group. n refers to numbers of repetition.
Coefficient of variation:

$$C = \frac{S}{\bar{X}} \times 100\% \tag{2}$$

In the formula: $\bar{X}$ is the average weight of 100 seeds (g).

According to the data in Table 1, $\bar{X}$ = 84.13, $\sum X^2$ = 56679, $(\sum X)^2$ = 452929.
According to formula (1), standard deviation:

$$S = \sqrt{\frac{8 \times 56679 - 452929}{8 \times (8-1)}} = 2.99$$

According to formula (2), coefficient of variation:

$$C = \frac{2.99}{84.13} \times 100\% = 3.55\%$$

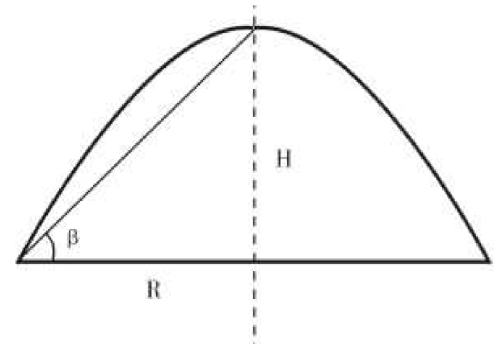


Fig. 1: Schematic diagram of measuring natural angle of repose

If coefficient of variation is not exceeding 4.0%, the calculation of thousand-seed weight may be in accordance with the measurement results. $10 \times \bar{X}$ refers to seeds thousand-seed weight, namely, 841.3 g.

The natural angle of repose: The natural angle of repose, also called the angle of rest, refers to the included angle formed between the cone slope and its bottom margin. The cone is formed when seeds are freely dropping on a plane from height (Tian *et al*., 2010).

It adopts the traditional straightness measurement, as shown in Fig. 1, using the fixed basal diameter. It only needs to measure the cone height of cyperus esculentus. So the angle of repose:

$$\beta = \arctan \frac{H}{R}$$

Of which H refers to the cone height and R refers to the cone basal radius. According to the abovementioned method, the seed angle of repose is 37°.

SEED-METERING DEVICE STRUCTURES AND WORDING PRINCIPLES

Suction components of the air suction seed-metering device are composed of vacuum chamber housing, discharge plate, friction-reducing seal ring, vacuum linking pipe and fan. When the air suction seed-metering device is in operation, the negative pressure produced by the high speed fan is transferred to seeding individual vacuum chamber. When the discharge plate is rotating, subjected to negative pressure of the vacuum chamber, it sucks seeds and rotates with the discharge plate. When seeds are rotated out of the vacuum chamber, they are no longer under the negative pressure and dropped into the furrow under the action of gravity or under the seed scraping device. It is shown in Fig. 2.

Theoretical calculation and determination of each structure parameter of the seed-metering device:

Seed discharge plate: The larger the vertical discharge plate is, the more numbers of suction openings can be arranged. It is helpful to cut its rotational speed and linear velocity of the discharge plate. But the oversized discharge plate will increase the dimension of seeding mechanism and seed suction chamber accordingly, as well as multiply the consumption of the fan. So the general diameter of the discharge plate is 140 mm-260 mm (Zhang, 1997), which is made of 1.2 mm thin stainless steel plate, diameter 200 mm. The seed suction opening has 0.2 mm-0.7 mm chamfers in the sidewall. Figure 3 shows the concise structure

Determining numbers of seed suction opening of the seed-metering device: Numbers of seed suction opening have intimate relationships with sowing speed and seed spacing. Without influencing the suction, seed scraping and falling, it is better to get more suction openings that are relevant to seeding performance. When the tractor driving speed is definite, with the increasing of seed suction openings, rotational speed of the discharge plate will be reduced. With prolonged contacting period of seeds and the discharge plate, seeding performance of the seed-metering device is gradually promoted. With increased seed suction openings, the distance between two openings becomes shorter and shorter. When openings increase to a certain value, two seed suction openings will influence each other, which will make seeds be arranged irregularly on the openings, so that it degrades the seeding performance.

Presently it is known that the suction openings on the discharge plate are of circular permutation and the Diameter (D) is 170 mm. The performance speed of the tractor (P) is P = 4 km/h, sowing seed spacing (S) is 10 cm. The linear velocity of current discharge plate suction opening is generally no more than 0.35 m/s.

The rotational speed of seed suction opening of the seed-metering device:

$$n = \frac{60v}{\pi D} \tag{3}$$

Of which, v refers to the linear velocity of the seed suction opening of the seed-metering device, v = 0.35 m/s.

D refers to the diameter of the suction opening in the discharge plate, being of circular permutation, D = 170 mm = 0.17 m.

According to formula (3):

$$n = \frac{60v}{\pi D} = \frac{60 \times 0.35}{3.14 \times 0.17} = 39.3rpm$$

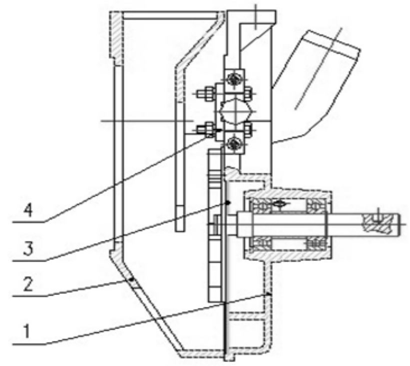


Fig. 2: Structure diagram of seed-metering device; 1: Cylinder assembly; 2: Seeds chamber; 3: Seeding plate; 4: Seeds cleaning device

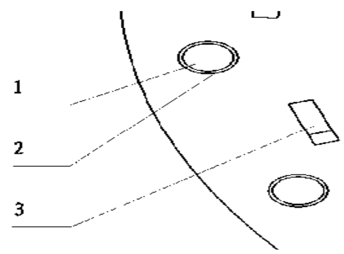


Fig. 3: Concise structure diagram of seed plate; 1: Suction opening; 2: Chamfer; 3: Mixing device

Numbers of seed suction openings:

$$N = \frac{P(1-\delta_r)}{A \cdot n} \tag{4}$$

Of which,

P = To the performance speed of the tractor, 4 km/h (66667 mm/min).

S = To sowing seed spacing, S = 100 mm.

n = To rotational speed of suction opening of the seed-metering device, n = 39.3 rpm.

δ_r = To the tractor's slip rate, δ_r = 2% (Ma *et al*., 1998):

$$N = \frac{P(1-\delta_r)}{A \cdot n} = \frac{66667 \times (1-0.02)}{100 \times 39.3} = 17$$

The theoretical linear velocity of the seed suction opening is $v \le 0.35$m/s. So the seed suction opening numbers $N \ge 17$. In the design, due to the larger diameter of the seed suction opening, to select overmuch opening will lead to much more air leakage of the chamber and will influence its performance. So it selects 18 suction openings on the discharge plate.

Shape design and calculation of the diameter of the seed suction opening:

Shape design of the seed suction opening: Considering large cyperus esculentus seeds, it makes 0.2 mm-0.7 mm chamfers at the suction side of the seed

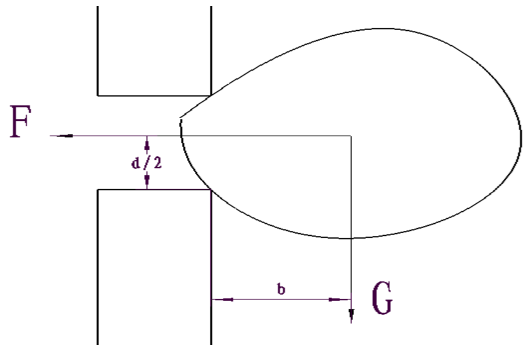


Fig. 4: Seed force analysis diagram without chamfer

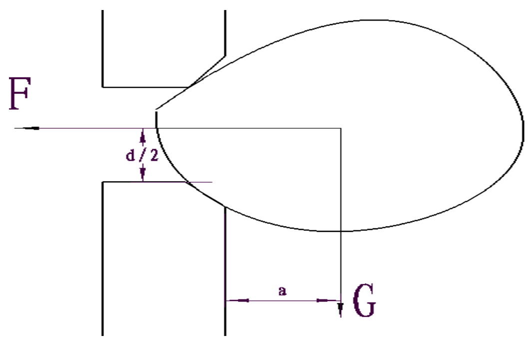


Fig. 5: Seed force analysis diagram with chamfer

suction opening. According to the force analysis with and without the chamfer in the Fig. 4 and 5, it shows that a<b. This chamfer is to reinforce the suction performance. Seeds that are sucked on the suction opening are not easy to fall off from the opening, even if they are crashed by other seeds in duration of the rotating on the discharge plate.

Determination of the seed suction opening diameter: As for the air suction seed-metering device, the larger is the diameter of seed suction opening, the better capacity of seeds suction has. The seeding performance is generally promoted. When the diameter increased to the definite value, the air pressure loss of the air chamber increases and the seeding performance reduces gradually. Therefore, to ensure the optimum seed-metering device performance, it selects proper seed suction opening diameter, which is determined by seed size of the sowing plant. Namely, $d = (0.64\text{-}0.66)\ b$, of which b refers to the average breadth of seeds (Dou *et al*., 1997). The average breadth (b) of cyperus esculentus is 9.8 mm, so seed suction opening diameter (d) is 6.5 mm.

The calculation of the suction chamber vacuum degree: In accordance with the following formula (Nanjing Agricultural University, 1996):

$$H_{c\max} = \frac{80K_1K_2CG(1+\frac{v^2}{gr}+\lambda)}{\pi d^3} \tag{5}$$

In this formula,

- K_1 = Suction reliability coefficient, value range 1.8-2.0, as for sphere-like tiny thousand-seed quality, it selects small value. Cyperus esculentus seeds take the shape of ellipsoid, so it selects $K_1 = 1.8$.
- K_2 = External condition coefficient, value range 1.8-2.0. As for larger thousand-seed quantity, it selects the larger value. $K_2 = 1.9$.
- C = The distance from seeds center of gravity to the discharge plate. It has a short distance due to the chamfer on the discharge plate. $C = 0.3$ cm.
- G = One seed gravity. Thousand-seed weight is 841.3 g, so one seed gravity G is 0.0082N.
- v = The linear velocity of seed suction opening of the discharge plate, $v = 0.32$ m/s.
- r = The radius of seed suction opening of the discharge plate, $r = 0.0085$ m.
- g = Acceleration of gravity, $g = 9.8$ m/s2.
- λ = Comprehensive coefficient of the seed frictional resistance, λ = (6~10) tan *a*. *a*. refers to seeds natural angle of repose, it measures that the natural angle of repose is 37°. So comprehensive coefficient of the frictional resistance $\lambda = 4.5$.
- d = The diameter of seed suction opening of the discharge plate, $d = 0.65$cm.

Therefore vacuum degree of the suction chamber is:

$$H_{c\max} = \frac{80K_1K_2CG\left(1+\frac{v^2}{gr}+\lambda\right)}{\pi d^3}$$

$$= \frac{80\times1.8\times1.9\times0.3\times0.0082\times\left(1+\frac{0.32^2}{9.8\times0.0085}+4.5\right)}{3.14\times0.65^3}$$

$$= 5.25\,KPa$$

PERFORMANCE TEST ANALYSIS OF THE AIR SUCTION SEED-METERING DEVICE

Test project: It determines the seeding performance of the device, namely, the single seed rate under different seed suction opening diameters. Due to the heavier thousand-seed weight of cyperus esculentus seeds, the precondition for the test is that the negative pressure in the suction chamber cannot be too low.

Test procedures:

- Before the test, it connects the fan with the seed-metering device, confirming that everything goes well. It starts the electric machinery, adjusting the rotational speed of the motor to 4500 r/min by control panel of three-phase motor. At that time the wind pressure is 6.5 kpa.
- According to the analysis to the seed suction opening diameter and numbers, it is known that the theoretical diameter is 6.5 mm and there are 18 seed suction openings. In the test it considers the

Table 2: The statistical result of test data

Bore diameter/mm	Re-suction rate /%	Miss-suction rate /%	Single seed rate /%
5.5	0	45.3	54.7
6.0	0	31.8	68.2
6.5	0	27.9	72.1
7.0	0.4	24.1	75.5
7.5	2.3	19.3	79.4

discharge plate that its different diameters are 5.5, 6.0, 7.0, 7.5 mm, respectively and there are 18 seed suction openings as comparison (Zhang *et al*., 2012).

- In duration of the test, experiment data are based on fixed-parameters: 18 seed suction openings, discharge plate rotational speed 30 r/min, fan rotational speed 4500 r/min and air chamber negative pressure 6.5 kpa. It rotates the seed-metering device of each diameter for 10 rounds and calculates single seed rate, re-suction rate, miss-suction rate of every diameter of each seed-metering device.
- Statistics results are shown in Table 2.

Experiment results analysis:

- The separator in the middle of the air suction seed-metering device separates seeds chamber from the discharge plate by some proper position to limit seeds position. But seeds have large natural angle of repose and poor flowability. Accordingly they are easy to be blocked in one side of the baffle to miss the suction of seeds.
- Whether cyperus esculentus can be adsorbed on the seed suction opening more depends on the quality of seeds flowability.

IMPROVEMENT DESIGN OF THE SEED-METERING DEVICE

In accordance with the above test results, it may be improved by two aspects as follows. Firstly, it tries to increase the contact area between seeds and the discharge plate and to ensure the contact period between the seed suction opening and the discharge plate. Secondly, due to poor seeds flowability, it installs the mixing device on the discharge plate to reinforce seeds flowability, so that seeds can be sucked on the seed suction opening in a better way. The structure is shown in Fig. 6. This seed-metering device ensures the full contact between the seed suction opening and seeds. Between the air chamber and the discharge plate, it added seal rings to ensure the air-tightness of the air suction seed-metering device and to reduce air pressure loss.

Perfection of the cover of the air suction seed-metering device: Seeds saving chamber is composed of part of the space inside the seed-metering device cover and the discharge plate to temporarily save seeds.

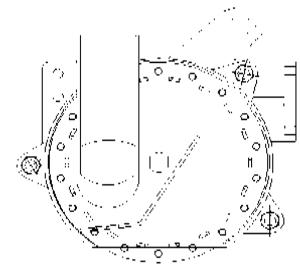
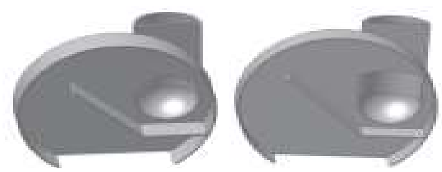


Fig. 6: Structure diagram improved seed-metering device



(a) (b)

Fig. 7: Comparison structure diagram of seed-mmetering device cover; (a): Former seed-metering device cover; (b): Improved seed-mmetering device cover

Poor seeds flowability is due to the uneven seeds surface and large seed size. Consequently seeds will be overhead at the contact of seeds conveyance pipe and seeds chamber. Aiming at this challenge, it shall modify the cover of the seed-metering device, increase the contact area of the grain tube and seeds chamber under the condition of guaranteeing seeds position, in order to prevent from being overhead. The sketch is shown in Fig. 7.

Design of the mixing device: The seed charging rate of the air suction seed-metering device depends on gas volume and seeds flowability. When gas volume is definite, seeds flowability directly influences the seed charging rate. Vertical disk type air suction seed-metering device adsorbs seeds from the side of the discharge plate. In duration of the suction, seeds shall be constantly filled into the seed filling component of the seed-metering device. But as for seeds of larger natural angle of repose, it is necessary to get external force, so that seeds are constantly conveyed nearby the seed suction opening of the discharge plate. This avoids the increase of miss-seeding rate because seed suction opening cannot suck seeds. Mixing mechanism is used to prevent from miss-seeding, to promote seeds mixing and seed charging rate.

The mixing device configuration is shown in Fig. 8a, the position on the discharge plate is shown in Fig. 8b.

Determination of the position of the mixing device on the discharge plate: When rotational speed of the seed-metering device is definite, the larger edge radius

(a) (b)

Fig. 8: Structure and position of mixing device; 1: Seed discharge plate; 2: Mixing device; (a): Mixing device, (b): Mixing device on the seed discharge plate

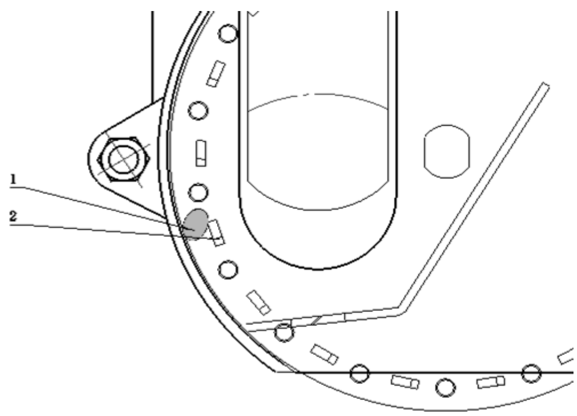


Fig. 9: Seed seizing-up situation by the mixing device; 1: Cyperus esculentus; 2: Mixing device

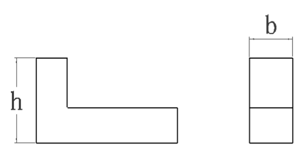


Fig. 10: Shape structure diagram of mixing device

of the mixing device on the discharge plate is, the larger the linear velocity. Consequently the mixing device may mix seeds in a better way and increase seeds flowability. But there formed a smaller space (s) between the mixing device and the inside of the seed-metering device cover. If the space (s) is smaller than the average breadth (b) of cyperus esculentus seeds, when the seed-metering device is in operation, the mixing device will be blocked by cyperus esculentus seeds. So that it doesn't work normally. It is shown in Fig. 9.

Therefore, under the condition that the seed-metering device is in good operation, the mixing device locates between two seed suction openings and the space (s), which is between the mixing device and the edge of the discharge plate, shall be larger than the average breadth (b) of cyperus esculentus.

Determination of the mixing device shape: The structure of the mixing device is determined by height (h) and breadth (b), as shown in Fig. 10.

Table 3: Table of factors and levels

Actors and levels	A h (mm)	B b (mm)
1	4	3
2	5	4
3	6	5

It carries out the orthogonal test to height (h) and breadth (b), as well as data reduction to test results, in order to find the optimal combination influencing the seeding performance of the seed-metering device. Tests are based on the discharge plate of the fixed-parameter: 18 seed suction openings, discharge plate rotational speed 30 r/min, fan rotational speed 4500 r/min, air chamber negative pressure 6.5 kpa. The seed-metering device of diameter 6.5 mm rotates 10 rounds at a uniform speed to determine the position of the mixing device on the discharge plate. It selects three levels of mixing device height h and breadth b to carry out the orthogonal test (Teng *et al*., 2008), adopting L9 (3^4) orthogonal form, experimental factor level choice is shown in the Table 3.

Orthogonal design plan is as the Table 4.

Orthogonal test results analysis: Implementing the orthogonal test scheme, it obtained the test data after calculation as Table 5.

In Table 5, $\bar{k}_1$, $\bar{k}_2$, $\bar{k}_3$ respectively refers to the average value of seeds suction under different factors in each level. *R* refers to the range of average suction rate under the same factor in each level. Table 5 shows that the optimum combination for better seeding performance is mixing device height (h) 5 mm and breadth (b) 3 mm.

Comparison testing with or without the mixing device: The mixing device shape and the position on the discharge plate are determined. To testify whether the mixing device can increase the seeds flowability, the design test is as follows:

- It selects the discharge plate, there are two openings of opening diameter 5.5, 6.0, 6.5, 7.0, 7.5 mm, respectively and are divided into two groups. In each group, on the discharge plate of each different diameter, it installs the mixing device with the fixed parameters.
- As in the test, it is based on the fixed parameters: 18 seed suction openings, discharge plate rotational speed 30 r/min, fan rotational speed 4500 r/min, air chamber negative pressure 6.5 kpa. Respectively it rotates the seed-metering device of each diameter for 10 rounds and calculates single seed rate, re-suction rate, miss-suction rate of each seed-metering device of different diameters.
- Statistics results are shown in the Table 6 and 7.

In accordance with the test data statistics it shows that: miss-suction rate and single seed rate of the

Table 4: The orthogonal experiment table

Test number/Factors	A Height of mixing device/h	B Weight of moxing device/b	A×B Interaction column	C Empty
1	1 (4)	1 (2)	1	1
2	1 (4)	2 (3)	2	2
3	1 (4)	3 (4)	3	3
4	2 (5)	1 (2)	2	3
5	2 (5)	2 (3)	3	1
6	2 (5)	3 (4)	1	2
7	3 (6)	1 (2)	3	2
8	3 (6)	2 (3)	1	3
9	3 (6)	3 (4)	2	1

Table 5: Analysis results of orthogonal test

Number	A	B	A×B	C	Test result
1	1	1	1	1	95.6
2	1	2	2	2	93.4
3	1	3	3	3	93.0
4	2	1	2	3	96.0
5	2	2	3	1	94.3
6	2	3	1	2	94.6
7	3	1	3	2	97.0
8	3	2	1	3	94.7
9	3	3	2	1	90.1
$\bar{k}_1$	94.0	96.2	95.0	93.3	
$\bar{k}_2$	95.0	94.1	93.2	95.0	
$\bar{k}_1$	93.9	92.6	94.8	94.6	
Rang (R)	1.1	3.7	1.8	1.7	
Primary and secondary order	$B > A\times B > A$				
Optimal level	A_2	B_1			
Optimal combination	A_2B_1				

Table 6: Test data statistics of different aperture seed plate without mixing device

Bore diameter/mm	Re-suction rate/%	Miss-suction rate/%	Single seed rate/%
5.5	0	34.3	65.7
6.0	0	21.7	78.3
6.5	0	19.4	80.6
7.0	1.4	14.1	84.5
7.5	5.3	12.3	82.4

Table 7: Test data statistics of different aperture seed plate with mixing device

Bore diameter/mm	Re-suction rate/%	Miss-suction rate/%	Single seed rate/%
5.5	0	12.3	87.7
6.0	0.6	9.4	90.0
6.5	1.8	2.3	95.9
7.0	9.6	1.2	89.2
7.5	15.2	0.8	84.0

discharge plate installed with the mixing device are much better than that without the mixing device. It promotes seeds flowability in a better way. Moreover, in the discharge plate installed with the mixing device, when the diameter is 6.5 mm, the seed-metering device has the optimism seeding performance.

CONCLUSION

The unmodified seed-metering device has poor operation performance. The separator between the seed tank and the discharge plate is possible to jam seeds, which seriously influenced the suction rate. The modified seed-metering device increases the contacting area between seeds and the discharge plate and reduces the omitted-suction rate of seeds.

It designs a mixing device installed on the discharge plate, through the orthogonal experiment it gets the best geometric dimensioning of the mixing device, height (h) = 5 mm, breadth (b) = 3 mm. It determines the installation position of the mixing device on the discharge plate.

Through comparison testing that whether there is the mixing device or not on the discharge plate, it concludes that the discharge plate with the mixing device is likely to increase seeds flowability and to promote the seed charging rate of seed-metering device. Finally it determines that the mixing device with the discharge plate has the best seeding performance when the seed suction opening diameter is 6.5 mm.

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