

# DESIGN AND EXPERIMENT OF SMALL VEGETABLE SEEDER WITH SINGLE DISC MULTI-ROW SEEDING AND INDEPENDENT AIRWAY

## 小型单盘多行独立气道蔬菜播种机设计与试验

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### ABSTRACT

*In this paper, a small pneumatic vegetable precision seeder suitable for facility greenhouses was designed. Based on the traditional positive and negative pressure seed-metering device, the airway disc structure was designed, and the negative pressure air chamber was divided into three separate air chambers. The separate air chambers could solve the problems of high-pressure requirements of traditional seed-metering device with large air chamber and suitable for small power machineries more. One, two, or three rows drill can be completed by replacing the seed plate and divider. The seed discharge process of the seed-metering device was analyzed and the bench test was performed. Results showed that the required pressure of the seed-metering device with the airway disk was 1 kPa less than traditional seed-metering device with large air chamber when the eligible rate of seed discharge was 95%. Field experiments were performed, results showed that the best performance were achieved under the speed of 3 km/h, for 3.72 % missed, 1.93% repeat and 94.35 % of inner ring, and 5.72%, 1.87% and 92.41% respectively of outer, meeting the requirements for vegetable seeding.*

### 摘要

本文设计了一种适用于设施大棚的小型气力式蔬菜精量播种机，在传统正负压排种器的基础上，设计气道盘结构，将负压气室分为3个独立的气室，解决传统正负压排种器气室大，气压要求高，不适合小动力机械的问题。通过更换排种盘和分种器，可以完成1行、2行或3行蔬菜播种作业。对排种器排种过程进行了分析和台架实验，结果表明，满足排种合格率95%时，带有气道盘的排种器所需气压比传统排种器小1kpa。对设计的小型单盘多行独立气道蔬菜播种机进行田间试验，结果表明：播种速度为3km/h时，播种效果最佳，此时内圈漏播指数为3.72%，重播指数为1.93%，合格指数为94.35%；外圈漏播指数为5.72%，重播指数为1.87%，株距合格率为92.41%，满足蔬菜播种要求。

### INTRODUCTION

Facility agriculture is an important part of modern agriculture. At present, China has become a major country in facility agriculture, with the largest planted areas and most output of vegetables in the world (Xiao *et al.*, 2017; Chen *et al.*, 2018; Yazgi A *et al.*, 2014). However, compared with developed countries, the mechanization level of facility agriculture was relatively low, with the comprehensive mechanization level was only about 30% and the planting mechanization level was only 15.2% (Li *et al.*, 2021; Qi *et al.*, 2020; Li *et al.*, 2014). Due to the small space of the facility's greenhouse, large pneumatic vegetable planters could not be brought into operation. Vegetable seeding was usually done by manual or small simple mechanical seeder, which have low accuracy and high labor intensity, severely limiting the level of mechanization in facility farming.

At present, the research of vegetable seeder in developed countries in Europe and America are mainly focused on vegetable seeding machinery in large field, which can realize many functions such as ditching, seeding, soil covering and drip irrigation belt laying, but with large power and high sales price, which is not suitable for facility greenhouses. An air-suction vegetable seeder from Maschio, for example, can produce precise seeds of different sizes by changing seed plates with different apertures. While research in Asian countries like China, Japan and South Korea are focusing on small and medium-sized mechanical vegetable planters, which are compact and lightweight and more suitable for facility greenhouses.

For example, Hu Jingming et al. in China designed the hand-held precision acupoint planter for rapeseed, and the disc vegetable planter produced by Borante in Korea, etc. But mechanical seed planters have a high seed damage rate and low accuracy for irregular seeds and are suitable for granulated seeds (Hu et al., 2017; Jafari et al., 1991; Maleki et al., 2006).

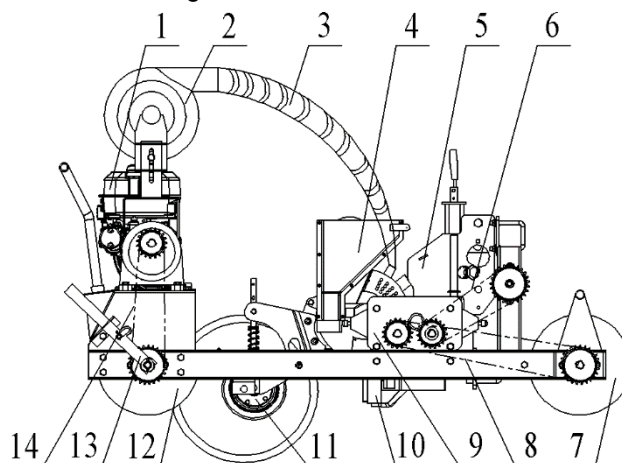
In this paper, for the demands of vegetable precision seeding in facility greenhouses, a vegetable seeder was designed, whose seed-metering devices had single disc but multi-row seeding and independent airway. And the airway disc was innovatively designed based on the traditional positive and negative pressure seed-metering device, which reduced the negative pressure chamber and low pressure needs for seed suction and avoided the problem of miss-seeding caused by insufficient fan speed because of the insufficient power of the small machine. The seeder designed in this paper could improve the accuracy of vegetable sowing and promote the mechanization level of facility agriculture.

## MATERIALS AND METHODS

### Overall structure and working principle

As shown in Fig. 1, the overall structure of the vegetable seeder mainly includes the frame, seed-metering device, ditching and seed division device, row suppression device, front and back suppression device, depth adjustment device, plant spacing adjustment transmission, fan and power system.

The gasoline engine power was divided into two ways, one through a chain drive back suppression wheel which drives the whole machine, while the front suppression wheel was rotated passively and drove the seed-metering device through the gearbox and chain. When travelling on road, the gearbox was in neutral, and the seed-metering device didn't work. And when seeding in the facility greenhouse, the gearbox was adjusted in the position rely on the seeding space requirements, while the seed-metering device was rotated. The other power part from gasoline engine drove the fan by belt. The fan connected with air pipe, which provided stable air flow to the seed-metering device.



**Fig. 1 - Complete machine structure diagram**

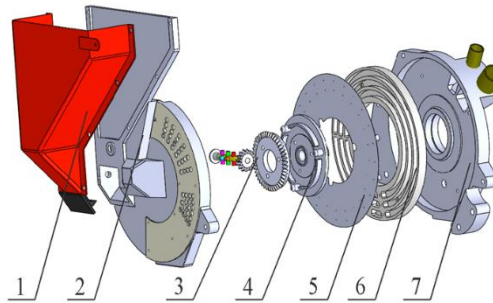
1. Gasoline engine; 2. Fan; 3. Positive pressure air duct; 4. Seed-metering device; 5. Depth limit and adjustment device; 6. Transmission chain; 7. Front suppression wheel; 8. Seed-metering device drive chain; 9. Gearbox; 10. Ditching and seed division device; 11. Row suppression device; 12. Back suppression wheel; 13. Clutch; 14. Walking driven chain.

### Seed-metering device structure and principle

Seed-metering device is the key component of the whole machine, which directly determines seeding accuracy and working efficiency (Wang et al., 2020; Zhang et al., 2011; Jiang et al., 2014). Pneumatic seed-metering devices have been widely used in the vegetable sector due to their good adaptability to seed shapes, little damage, and high accuracy and uniformity. For example, Zhang Kaixing et al. (Zhang et al., 2019) designed an air suction seed-metering device with double-disc for vegetable, which can achieve precise seeding for different sizes seeds, but it is easy to produce sticky disk phenomenon when seeds fall by seed weight for light vegetable seeds. Cong Jinling et al. (Cong et al., 2014) designed a seed-metering device with positive and negative pressure, which relied on negative pressure to fill seeds, and blew the seeds off through increasing positive pressure at the seed dropping site, thus solving the problem of seed sticking disc. However, conventional air suction seed-metering device could only plant one row, which was difficult to meet the requirements of leafy vegetable seeding with small row spacing. Yan Qiuyan et al. (Yan et al., 2014) developed a pneumatic seed-metering device which could realize two-row seeding.

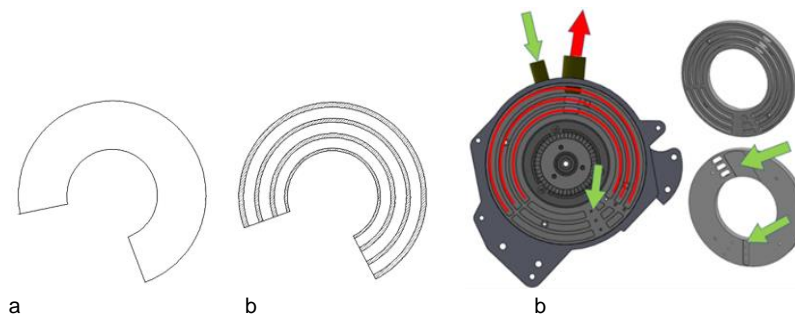
However, the structure of the seed-metering device was complicated with two seed plates and the two seed plates share one air chamber, which requires high pressure. Li Ming et al. (Li et al., 2013) developed a pneumatic aggregate precision seed-metering device for rape, which could plant multiple rows by one device, but it was suitable for the field traction vegetable planter, which had a large power demand.

Aiming at the requirement of small row space for vegetable seeding, seed-metering devices having single disc but multi-row and independent airway was designed as shown in Fig. 2. The airway disc was the core component of the metering device. The traditional air chamber shown in Fig. 3a which required higher air pressure to ensure the stability of seed absorption (Wu et al., 2007) was divided into independent airway by airway disc shown in Fig 3b which reduced the demand for air pressure, and only negative pressure was passed in the airway corresponding to the seed suction hole but positive pressure was at the seed dropping mouth shown in Fig 3c, so as to solve the problem of miss-seeding caused by limited power and insufficient air pressure of the small seeder.



**Fig. 2 - Structure diagram of seed meter**

- 1. Seed box; 2. Shell; 3. Seed stirring device; 4. Power plate; 5. Seed arrangement plate; 6. Airway plate; 7. Right shell of seed discharging device

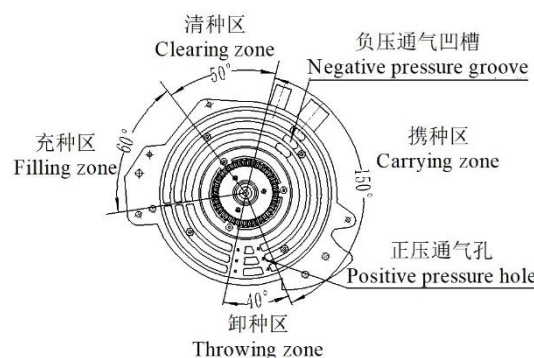


**Fig. 3 - Schematic diagram of airway disc structure**

- 1. Negative pressure annular groove; 2. Negative pressure ventilation groove;
- 3. Positive pressure groove; 4. Positive pressure vent hole;
- A: Conventional air chamber; B: Independent chamber; C: Airway disk structure and flow route map

**Analysis of seeding process**

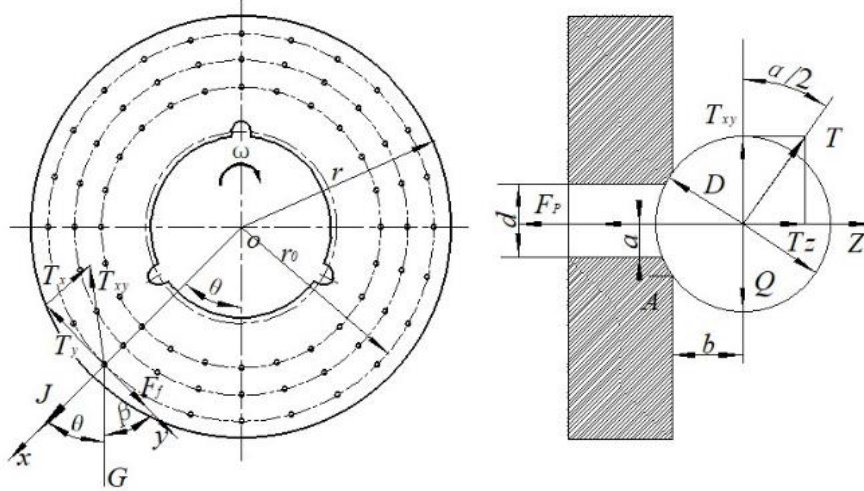
According to the different functions of each region during seeding, the working area of the seed-metering device was divided into four regions: seed filling region, seed clearing region, seed carrying region, and seed unloading region, as shown in Fig.4. According to Bernoulli equation, the pressure was equal everywhere in the constant chamber flow field (Li et al., 2012; Chen et al., 2007).



**Fig. 4 - Partition of seed-metering device working area**

**(1) Seed filling process analysis**

Ignoring the effects of machine vibrations and other factors in the seeding process, rape seeds with a good spherical shape were chosen as the objects of study, and outer ring seeds were used as particle points to establish a Cartesian coordinate system. The direction of the centrifugal force on the seed was taken to be the positive direction of the x axis, the direction of air and friction between seeds was taken as the positive direction of y axis, the direction of the normal vector of the seed plate was taken to be the positive direction of the z-axis, the kinematic analysis of the seed filling process was shown in Fig. 5.



**Fig. 5 - Force analysis of suction seed course**

Note:  $G$  is seed gravity,  $N$ ;  $J$  is centrifugal force of seeds,  $N$ ;  $F_f$  is frictional resistance between air and seeds,  $N$ ;  $Q$  is resultant force of  $G$ ,  $J$  and  $F_f$  of seeds,  $N$ ;  $T$  is normal force of suction hole to seeds,  $N$ ;  $T_x$ ,  $T_y$  and  $T_z$  are component force of  $T$  on the  $x$ ,  $y$  and  $z$  axis,  $N$ ;  $T_{xy}$  is resultant force of  $T_x$  and  $T_y$ ,  $N$ ;  $F_p$  is suction force of seed,  $N$ ;  $\omega$  is angular speed of seed-metering plate,  $\text{rad}\cdot\text{s}^{-1}$ ;  $O$  is center of seed-metering plate;  $\theta$  is included angle between attachment from seed barycenter to seed-metering plate center and vertical direction, ( $^\circ$ );  $\beta$  is included angle between gravity and  $y$ -axis, ( $^\circ$ );  $r$  is radius of seed-metering plate,  $m$ ;  $r_0$  is radius of the circle surrounded by the outer holes,  $m$ ;  $D$  is diameter of seed,  $m$ ;  $a$  is distance from action point to suction axis,  $m$ ;  $b$  is distance from action point to resultant force  $Q$ ,  $N$ ;  $d$  is diameter of suction hole,  $m$ ;  $\alpha$  is taper angle of suction hole, ( $^\circ$ ).

The stress balance equation of rape seeds in the filling process was as in formula (1).

$$\begin{cases} \sum F_x = 0, T_x - G \cos \theta - J = 0 \\ \sum F_y = 0, T_y - G \sin \theta - F_f = 0 \\ \sum F_z = 0, T_z - F_p = 0 \\ \sum M_A = 0, F_p a - Qb = 0 \end{cases} \quad (1)$$

According to formula (1), binding force on seeds in the XY plane during seed filling can be expressed as formula (2).

$$T_{xy} = \sqrt{T_x^2 + T_y^2} = \sqrt{G^2 + J^2 + F_f^2 + 2G\sqrt{(J^2 + F_f^2)} \sin(\theta + \beta)} \quad (2)$$

If the seed was balanced at the suction hole, then:

$$F_p = Qa/b = Q \tan(\alpha/2) = T_{xy} \tan(\alpha/2) = \sqrt{G^2 + J^2 + F_f^2 + 2G\sqrt{(J^2 + F_f^2)} \sin(\theta + \beta)} \times \tan(\alpha/2) \quad (3)$$

The critical value of negative pressure vacuum degree at the seed suction hole was simulated as formula (4).

$$P = \frac{F_p}{S} = \frac{4\sqrt{G^2 + J^2 + F_f^2 + 2G\sqrt{(J^2 + F_f^2)} \sin(\theta + \beta)} \times \sin(\alpha/2)}{\pi D^2 \cos^3(\alpha/2)} \quad (4)$$

where:

$P$  - the theoretical negative pressure value at which the seed can be adsorbed in the filling process, kPa;

$S$  - the force region of the seed on the suction hole, m<sup>2</sup>.

In practice, seeds were subject to external factors such as air resistance, self-vibrations, and inconsistent seed sizes and shapes. To ensure the reliability of seed suction, the actual minimum vacuum degree of negative pressure during seed suction was as formula (5).

$$P_{0\min} = K_1 K_2 P = K_1 K_2 \frac{4\sqrt{G^2 + J^2 + 2G\sqrt{(J^2 + F_f^2)}\sin(\theta + \beta)} \times \sin(\alpha/2)}{\pi D^2 \cos^3(\alpha/2)} \quad (5)$$

where:

$K_1$  is coefficient of external conditions. (The external influence coefficient accounts for air resistance, external vibrations, and other factors that affect the seed suction process,  $K_1$  is generally 1.8 ~ 2, take  $K_1=1.8$ );

$K_2$  is suction reliability coefficient. (To compensate for errors due to seed size, shape, and inter-specific collisions,  $K_2$  is generally 1.8 ~ 2, take  $K_2=2$ ) (Li et al., 2009).

According to Equation (5), in the process of seed filling, the negative pressure required by the negative pressure gas chamber was related to the angle of seed suction hole, seed linear velocity (determined by the rotation speed of seed disc and the radius of seed suction hole), physical and mechanical characteristics of seeds and other factors.

## (2) Seed charging process analysis

At seed charging process, the adsorption force of the negative pressure air chamber on the seed vanished, and the positive pressure acted on the seed through the vent hole. At this point, the seed was affected by its own gravity  $G$  and barotropic pressure  $F$  (Li et al., 2009). Depending on the magnitude of positive pressure on the seed, the seed charging process was divided into active falling and forced falling.

### a. Active falling process analysis

If the positive pressure was enough for the seed to fall out of the suction hole and into the *seed division device*, it was an active falling. It took a certain amount of time for the seed leaving the seed plate to enter the *seed division device*. When the positive pressure was low, the horizontal acceleration and horizontal displacement of the seed were small, and the motion trajectory of the seed was dotted line *b* shown in Fig. 6.

The horizontal displacement of the seed was increased by the increasing of positive pressure when the displacement increased to the point where it collided to the shell, the seed bounced back, and the trajectory was dotted line *c*. When the positive pressure continued to increase, the seed had multiple collisions between the *seed plate and the shell*, and the trajectory was dotted line *a*.

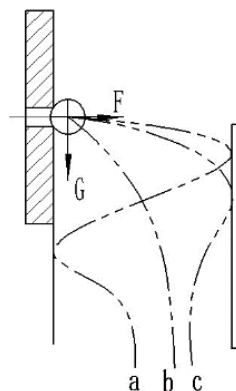


Fig. 6 - Active falling trajectory

Assuming that the positive pressure only generated an instantaneous shock force on the seed during seed dropping, and there was no longer pressure when the seeds removed from the seed suction hole. The velocity of seeds removed from the seed plate was equal to that before (Yong et al., 2015), then according to Newton's second law the trajectory of the seed during seed dropping can be represented by the equation (6).



$$\begin{cases} ma = F \\ \frac{1}{2}at^2 = l \\ vt + \frac{1}{2}gt^2 = H \\ PS = F \\ l < L \end{cases} \quad (6)$$

where:

$m$  is the weight of seed, (kg);  $F$  is the instantaneous force of positive pressure on the seed through the suction hole, (N);

$t$  is the time from seed breaking away from the seed plate to getting out of the seed-metering device, (t);

$l$  is the horizontal displacement of the seed, (m);

$v$  is the vertical velocity of the seed at the moment of its release from the seed plate, (m/s);

$H$  is the vertical displacement of the seed, (m);

$L$  is the distance between the two seed outlets, (m);

$P$  is the positive pressure zone, (Pa);

$S$  is the bearing area of seed, (m<sup>2</sup>).

According to equation (6), it was deduced that the positive pressure should satisfy equation (7).

$$\begin{cases} 0 < P < \frac{2mL}{Q^2S} \\ Q = \frac{-2v \pm \sqrt{v^2 + 2gH}}{g} \end{cases} \quad (7)$$

#### b. Forced falling process analysis

If the positive pressure couldn't meet the minimum requirement for seed active falling and couldn't blow the seed away from the suction hole, and if the seed could not be dropped by gravity alone, the seed continued to rotate with the seed plate, rotate towards the seed guide plate to forcibly scrape off the seed, and fall tightly into the seed separator below. One, two, or three rows of seeding with a seeder was completed. The structure of the seed guide plate and seeding apparatus is shown in Fig. 7.

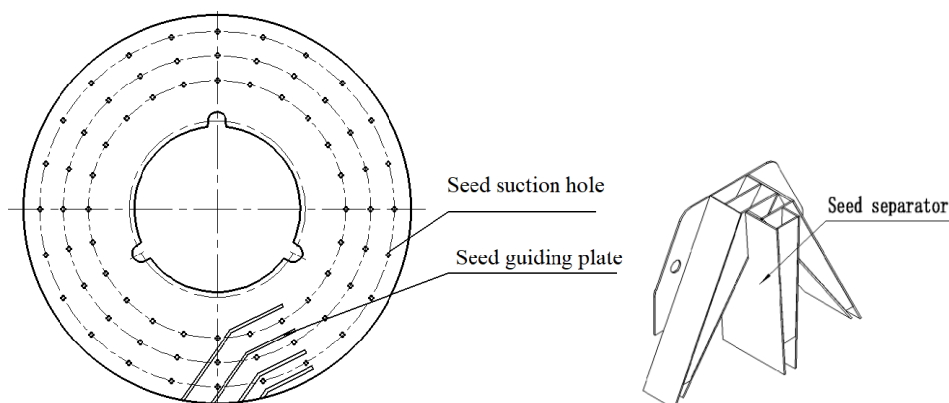


Fig. 7 - The structure of seed guiding plate and seed separator

## RESULTS

### Bench experiments

In order to explore the effect of the airway disc on reducing the negative pressure, a bench contrast test was carried on the JPS-12 seed-metering device performance testbed, the seed-metering device with and without airway disc was used to make a comparison, as shown in Fig. 8.

Rape seeds and a seed disc with 1 mm suction hole were selected and the experiments were carried under the condition that the seed plate rotational velocity was 15 r/min. Eligibility rates, leaky absorption rates, and re-absorption rates were as the evaluation metrics, and the results of the tests were shown in Table 1.



Fig. 8 - JPS—12 seed-metering device performance testbed

Table 1

Contrast test results of air chamber structure						
Air chamber structure	Index (%)	Negative pressure (kPa)				
		1.0	1.5	2.0	2.5	3.0
With airway disc	Qualified rate	94.6	95.22	95.47	93.61	91.38
	Miss-seeding rate	2.89	2.34	0.96	0.45	0
	Reseeding rate	2.51	2.44	3.57	5.94	8.62
With no airway disc	Qualified rate	89.4	90.26	94.63	95.13	95.36
	Miss-seeding rate	10.2	8.61	3.05	2.46	2.03
	Reseeding rate	0.4	1.13	2.32	2.41	2.61

Experimental results shown that for negative pressure of 1 kPa, the qualified rate of seed-metering devices with airway disc reached more than 90% and as the negative pressure increased to 1.5 kPa and 2.0 kPa, the qualified rate was over 95%. However, when the negative pressure reached 2.5 kPa, the reseeding rate was high, resulting in a drop in the qualified rate. In contrast to traditional seed-metering device which with no airway disc, as the negative pressure increased, the miss-seeding rate gradually decreased, the reseeding rate slightly increased, and the qualified rate was in increasing trend. When negative pressure reached 1.5 kPa, the qualified rate reached more than 90%, and more than 95% when the negative pressure reached 2.5 kPa, which pressure was 1kPa higher than that with airway disc. The results indicated that the airway disc structure could effectively reduce the suction negative pressure.

**Field experiment**

Field tests were carried on in Fuqun Agricultural Machinery Professional Cooperative in Linz on February 29, 2023, the seeder with two seed-metering devices with airway discs and had two circular suction holes on the discs, as shown in Fig. 9. The commercially available cilantro seeds were selected, the theoretical plant spacing was set to 5 cm, and the operating speeds were set to 2 km/h, 3 km/h, and 4 km/h respectively. After seeding, a 2 m long seeding section was randomly selected from each row and 20 measurement points were selected according to "GB/T6973-2005 Testing methods of single seed drills (precision drills), the plant spacing, qualified rate, miss-seeding and reseeding rate were determined, and the test results were shown in Table 2.



Coriander seeds



Seeder



Test after seeding

Fig. 9 - Prototype field test

Table 2

Calculation result of performance index of small pneumatic precision planter for vegetable						
Speed Index	2 km/h		3 km/h		4 km/h	
	Inner ring	Outer ring	Inner ring	Outer ring	Inner ring	Outer ring
Qualified rate (%)	93.29	91.59	94.35	92.41	90.61	90.16
Miss-seeding rate (%)	2.84	4.16	3.72	5.72	7.68	8.63
Reseeding rate (%)	3.87	4.25	1.93	1.87	1.71	1.21

The test results showed that all qualified rates reached 90% under three speeds. However, the miss-seeding rates were increasing and the reseeding rates were decreasing as the speeds increased. And the miss-seeding rate increased but reseeding rate decreased dramatically under the speed of 4 km/h. The best performance speed was 3 km/h, but there was certain gap compared to the performance on the bench test, as the actual field operation of the seeder was affected by its own vibrations, soil environment, and other factors. In addition, the qualified rates of the outer ring were lower than that of the inner rings similar with those on the bench test. As the seeds in the outer ring were subjected to a greater centrifugal force, the phenomenon of miss-seeding was easily produced. In order to solve the problem, the size of annular grooves corresponded with the outer ring could increase, to balances the forces and reduce the miss-seeding rates in subsequent improvements.

## CONCLUSIONS

(1) A small vegetable seeder with single disc but multi-row seeding was designed. The independent airway disc was innovatively designed base on the traditional pneumatic seed-metering device which could decrease the negative pressure. The bench test results showed that the negative pressure value was lower by 1 kPa when the airway disc was used than that of the traditional pneumatic seed-metering device when qualified rate reached 95%.

(2) Field experiments of the small vegetable seeder were carried on, results shown that it was the optimum operation in a seeding speed of 3 km/h, while the miss-seeding rate was 3.72 %, the reseeding rate was 1.93 % and the qualified rate was 94.35% for the inner ring, and 5.72%, 1.87% and 92.41% respectively for the outer ring. The seeder meets the requirements for vegetable seeding.

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