Design and experimental study of the fertilizer applicator with vertical spiral fluted rollers

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Abstract: To improve the uniformity and accuracy of fertilizing amount for fertilizer applicators with spiral fluted roller, this paper experimentally studied the influence of major structural parameters on the fertilizing performance. Through two sets of orthogonal tests, it is found that the helix angle and installation angle of spiral fluted rollers are the main factors, which affect the uniformity of fertilizer discharge and the linear relationship between fertilizing amount and opening, respectively. Based on these findings, the experiment and analysis were carried out to determine the optimal helix angle and installation angle for the spiral fluted roller The experimental results of fertilizing performance show that: when the helix angle is 45°, it able to achieve satisfactory uniformity of fertilizer discharge and linear relationship between fertilizing amount and rotational speed; when the installation angle is 40°, it enhances the accuracy of fertilizer discharge with good linear relationship between fertilizing amount and opening. Compared with the fertilizing performance of traditional fertilizer applicators with horizontally installed straight fluted roller, in the aspect of uniformity, the optimized fertilizer applicators reduce the variation coefficient of fertilizing amount within 0.2 s at low speed (10-30 r/min) from 5.1%-52.5% to 4.2%-14.7%; in the aspect of accuracy; and increase the correlation coefficient square R^2 between fertilizing amount and opening from 0.93-0.97 to no less than 0.996, and the regression intercept in the fitting equation is reduced from larger than 10.0 to less than 1.0.

Keywords: fertilizer applicator, spiral fluted roller, helix angle, orthogonal test
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1 Introduction

The variable-rate fertilization technology plays an important role in the precision agriculture system[1]. It able to save the production cost and reduce the environmental pollution by increasing the utilization efficiency of fertilizer[2]. Besides, the yield of crops can be promoted by optimizing the amount of fertilizer application based on comprehensively consideration on the information of soil condition, crop growth and yield[3,4]. To meet with the high requirements in the uniformity and precision of fertilization for the agronomy such as precision direct seeding of rice[5,6], fertilizer applicators with fluted rollers are increasingly attracting the attention of academia and industry, for the sake of structure compact and control flexibility[7-10].

The shape of fluted roller is one of the main factors that affecting the uniformity of fertilizer discharge, thus many researchers focused on the structural improvement of fluted rollers. Tola et al.[11] improved the uniformity of fertilizing amount by properly selecting the structural parameters of the straight fluted roller including radius, number of slots, slot type and openings. Kim et al.[12] studied on the intermittent straight fluted roller, and designed the segmented type of fluted roller with the axially arranged sheaves are staggered in the circumferential direction. Bangura et al.[13] compared the spiral fluted roller with the straight fluted roller through numerical simulation, and found the advantage of spiral fluted roller in controlling fertilizing amount. Meanwhile, some numerical studies of spiral fluted rollers concerned on the interaction between fertilizer particles and the components of fertilizer applicators, as well as the movement characteristics of fertilizer particles[14-16]. Few researches systematically analyzed on the uniformity of fertilization under different structural parameters on experiments.

In terms of the accuracy of fertilizer discharge, some researchers studied on the control of fertilizing amount by adjusting the opening of fluted roller, which can be tuned via an axial sliding sleeve[17] or a movable baffle[18] Some earlier studies[19,20] pointed out that the linear correlation between the fertilizing amount and the opening is not high enough, so that it is difficult to control the fertilizing amount accurately through the opening. Recently, Zhao et al.[21] proposed a vertically installed fluted roller, and studied the relationship between different installation angles and the correlation coefficient square R^2 between fertilizing amount and opening, which indicated that the installation angle of the fluted roller can affect the accuracy of fertilizing amount under the opening control. Even though, the above researches provide significant references for

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optimizing the installation of fluted rollers, further in-depth research is still needed to comprehensively consider the structural optimization of fluted rollers.

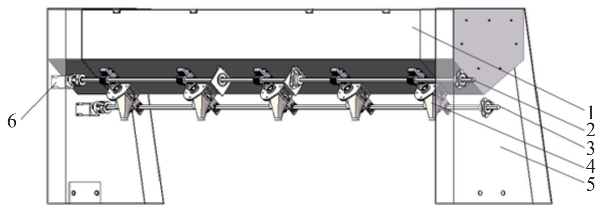
In our previous work, by conducting the numerical and experimental tests on the motion layer of fertilizer in spiral fluted rollers, Zeng et al.[22] found the driving layer was one of the key factors that affect the accuracy of fertilization and improved the structural design of the spiral fluted roller including: fertilizer-filling angle, fertilizer-contact angle and fertilizer-resistance angle, which increased the correlation coefficient square R^2 between fertilizing amount and rotational speed to be larger than 0.999. Later, Chen et al.[23] performed a bi-variable control of the rotational speed and opening of spiral fluted rollers, which achieve higher accuracy of fertilizing amount than those under the opening control only. Based on the fertilizer applicator design in these previous works, this paper took more structural parameters into consideration to further optimize the structural design of spiral fluted rollers for improving fertilizing performance.

The main factors that effect on the uniformity and accuracy of fertilizer discharge were analyzed through orthogonal test at the early stage, and the helix angle and installation angle were confirmed as the key influencing factors. Then, the helix angle and installation angle of the spiral fluted roller were optimized based on an all-factor test.

2 Structure and working principle of fertilizer applicator

2.1 Structural design

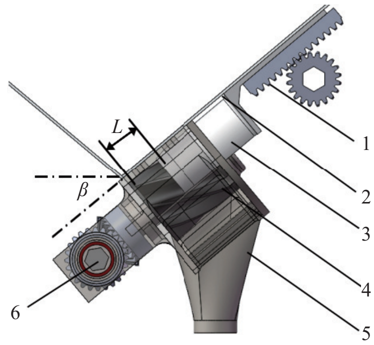
The installation diagram of fertilizer applicator with spiral fluted roller is shown in Figure 1. The rotational speed and opening of the fluted roller are controlled by two shafts respectively, which can also be controlled by other parallel or separate mechanisms. As the fertilizer applicator given in Figure 2, its main components involve opening control mechanism, speed control mechanism, spiral fluted roller, opening baffle and housing assembly. The opening control mechanism is composed by rack and pinion mechanism. The rotating speed control mechanism is a pair of 90° bevel gears, which transfers the rotating speed of the main shaft to the spiral fluted roller at a ratio of 1:1. The housing assembly is developed by the research group in South China Agricultural University. There is no driving layer formed when the fertilizer is discharged, which avoid the interference of the driving layer on fertilizing amount. The linear relationship between the fertilizing amount and rotational speed is strengthened, to achieve more accurate and controllable fertilizing amount.



1. fertilizer can; 2. opening control mechanism; 3. rotational speed control mechanism; 4. housing assembly; 5. fertilizer can holder; 6. drive motor

Figure 1 Installation of fertilizer applicator with vertical spiral fluted roller

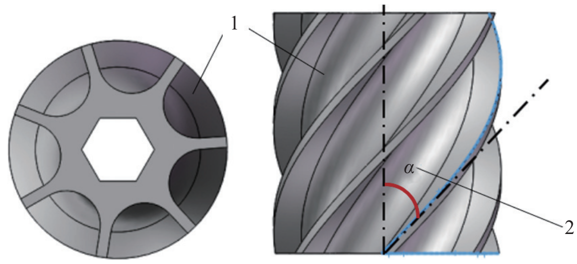
The opening L is the length of the fertilizer wheel that does not covered by the opening baffle, and the installation angle β is the angle between the shaft of spiral fluted roller and the horizontal plane (Figure 2).



1. opening control mechanism; 2. speed control mechanism; 3. opening baffle; 4. spiral fluted roller; 5. housing assembly; 6. rotational speed control mechanism

Figure 2 Structure of fertilizer applicator with spiral fluted roller

The structure of the spiral fluted roller is shown in Figure 3. The main factors affecting the uniformity of fertilizer discharge was analyzed experimentally in the existing works. The results of orthogonal test showed that the fertilizing amount has good uniformity when the number of grooves is 7 and the diameter is set to 60 mm[24], and changing the shape of flute into circular arc or conical circular arc have little influence on the uniformity of fertilizer discharge[15]. Therefore, the diameter of the spiral fluted roller is 60mm, and the number of flutes Z is 7 in this work. According to the actual needs on the fertilizing amount, the flute is designed as a conical arc. The cross section of the flute is vertical axially, and the cylinder is cut along the helix of the cylindrical surface outside the roller to form a spiral fluted roller with helix angle α.



1.Helix groove; 2.Helix angle α

Figure 3 Structure of spiral fluted roller

2.2 Calculation of fertilizing amount

In the fertilizer applicator with spiral fluted roller, the fertilizer is filled into the flute by its gravity and the force applied by the roller, and is transported and discharged with the flute, as the detailed working principal presented in the work by Bangura et al.[13]. In the whole process, only the fertilizer located in forced layer moves with the flute. The fertilizing amount per circle q and the total fertilizing amount Q can be calculated by:

$$q = L\gamma S\psi z \quad (1)$$

$$Q = q\omega t \quad (2)$$

where, S is the cross-sectional area of a single flute, cm^2; L is the opening of fluted roller, cm; γ is the bulk weight of fertilizer, g/cm^3; z is the number of flutes; ψ is the filling coefficient of the flute; ω is the rotational speed of spiral fluted roller, r/s; t is the time of fertilizer discharge, s.

3 Performance index and test method

3.1 Performance index

The continuous grid method[15] is used to investigate the uniformity of fertilizer discharge, which measures the fertilizing amount per unit time within a short continuous time, and calculates the standard deviation or variation coefficient. The smaller variation coefficient, the more uniform the fertilizer discharge.

Suppose that the number of samples in a continuous unit time is n. The fertilizer quality of each sample is m_i(g); then the calculation of average mass $\bar{m}(g)$; standard deviation s and variation coefficient σ (%) are stated as:

$$\begin{cases} \bar{m} = \dfrac{1}{n}\sum m_i \\ s = \sqrt{\dfrac{1}{n-1}\sum (m_i - \bar{m})^2} \\ \sigma = \dfrac{s}{\bar{m}} \times 100\% \end{cases} \tag{3}$$

As the cross-sectional area of a single flute is 230 mm^2, according to Equations (1) and (2), the measured fertilizing amount M (g) can be calculated by:

$$M = 16.1\gamma\psi L\omega t \tag{4}$$

Under a constant speed, the linear relationship between the opening and fertilizing amount and between the speed and the fertilizing amount are affected by the change of the filling coefficient ψ. Under different conditions, the smaller the change of the filling coefficient ψ, the more accurate the fertilizer discharge.

The linear relationship between the opening of spiral flute roller at different installation angles and the fertilizing amount, as well as the linear relationship between the rotational speed and fertilizing amount are the main references on evaluating the fertilizing performance. SPSS 2.4 was used to generate the fitting equation and calculate the square of the correlation coefficient R^2.

$$\begin{cases} R_\omega^2 = \left(\dfrac{\sum_{i=1}^{n} (\omega_i - \overline{\omega})(Q_i - \overline{Q})}{\sqrt{\sum (\omega_i - \overline{\omega})^2} \sqrt{\sum (Q_i - \overline{Q})^2}} \right)^2 \\ R_L^2 = \left(\dfrac{\sum_{j=1}^{m} (L_j - \overline{L})(Q_j - \overline{Q})}{\sqrt{\sum (L_j - \overline{L})^2} \sqrt{\sum (Q_j - \overline{Q})^2}} \right)^2 \end{cases} \tag{5}$$

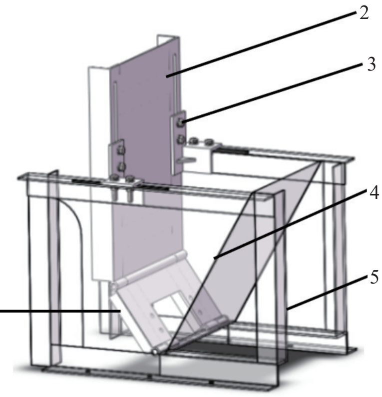
where, R_ω^2 is the square of the correlation coefficient between rotational speed and fertilizing amount; R_L^2 is the square of the correlation coefficient between opening and fertilizing amount; Q_i is the fertilizing amount at different opening; $\overline{Q}$ is the average fertilizing amount for all samples; L_j is the opening of fluted roller at different rotational speed; $\overline{L}$ is the average opening of fluted roller.

When R^2 is closer to 1 and the regression intercept a is closer to 0, it means the accuracy of the fertilizer discharger is higher.

3.2 Test method

In this paper, the helix angle α and installation angle β of spiral fluted rollers are studied. The 3D printer (FAST-JET-780) is adopted to manufacture the housing assembly and spiral fluted rollers with different helix angles by photosensitive resin and PC plastic material, respectively.

The movable side plate of fertilizer box with adjustable installation angle is designed as shown in Figure 4, which is composed of external frame, main box body, vertical plate fixed frame, movable vertical plate and movable side plate. The movable vertical plate is always vertical, and its relative position with the outer frame is fixed by the frame. The angle between the movable side plate and the horizontal plane can be freely adjusted between 0°-90°.



1. Movable side plate; 2. Movable vertical plate; 3. Vertical plate fixed frame; 4. Main box body; 5. External frame.

Figure 4 Structure of movable side plate of fertilizer box

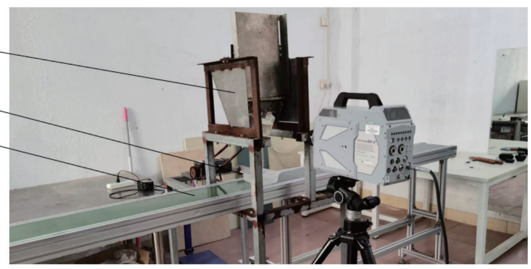
3.2.1 Continuous grid method

The continuous grid method is used to measure the uniformity of fertilizer discharge[24]. The method passes through the continuous grid continuously at the fertilizer discharge outlet under a certain speed, and the standard deviation or variation coefficient is calculated by measuring the fertilizing amount per unit time within a short period. The smaller the variation coefficient, the better the uniformity of fertilizer discharge.

There are 30 fertilizer boxes (length×width×height = 120 mm×50 mm×60 mm) pulled by the conveyor belt at a speed of 0.25 m/s and passed through the fertilizer outlet in turn to receive fertilizer. Each box contains fertilizing amount at 0.2 s. To avoid the disturbs caused by the acceleration delay of the conveyor belt at the start-up and shutdown, the first six and the last four boxes of fertilizer are discarded, and the remaining 20 boxes of fertilizer in the middle are taken as samples. Each group of tests was carried out three times and the average value of the three results was taken.

3.2.2 Measurement method of the fertilizing amount at different openings

The method is used to measure the fertilizing amount within 5 s. In order to avoid timing error of each fertilizer receiving, the conveyor belt timing is adopted. The fertilizer applicator is fixed. There are 4 fertilizer boxes (length×width×height = 180 mm×450 mm×80 mm) pulled by the conveyor belt at a speed of 0.18 m/s. The time for each box to receive fertilizer is 2.5 s (Figure 5). In order to avoid the errors caused by the acceleration delay of conveyor belt and fertilizer wheel at the start-up and shutdown, the first and last boxes are discarded, and the quality sum of fertilizer in the two middle boxes is taken as the sample. For each group tests are repeated for 5 times and the average value are taken as the results.



1. fertilizer applicator with spiral fluted roller 2. fertilizer box 3. conveyor belt

Figure 5 Measurement of fertilizing amount within 5 s

3.2.3 Test material

Three kinds of fertilizers with different material characteristics are selected for experimental study. A certain number of fertilizer particles are randomly selected, and their diameters are measured using a micrometer. The range of particle sizes was measured when the distribution ratio is more than 90%. Then, to calculate the compost density of the fertilizer, the fertilizer particles were randomly filled in a measuring cup, and their weight is measured by an electronic scale. Finally, the sliding angle of the fertilizer granules was measured using a digital inclinometer. The material characteristics of three kinds of fertilizers are given in Table 1.

Table 1 Material characteristics of the selected fertilizers

	Lardmee	Cnampgc	MCT
Particle size distribution (greater than 90%) /mm	2-3	3-4	1.5-4
Bulk density/g·mL^{-1}	979.3	944.8	937.9
Average slip angle/(°)	23.5	24.8	23.9

4 Design of structural parameters

4.1 Orthogonal test on the uniformity of fertilizer discharge

The coefficient of variation of fertilizing amount within 0.2 s for 20 consecutive times is set as the index to evaluate the uniformity of fertilizer discharge. The helix angle, rotational speed and opening of spiral fluted rollers are selected as the three major factors affecting the fertilization uniformity (Table 2).

Table 2 Selection of test factor level in orthogonal test

Level	Helix angle/(°)	Rotational speed/r·min^{-1}	Opening/mm
1	0	10	20
2	25	20	40
3	50	30	60

Since the obvious fluctuation of fertilizing amount is observed at low rotational speed and the lowest speed was usually set to no less than 20 r/min in the existing studies[15,16,18], this test also mainly focused on the uniformity of fertilization at low speed, the speeds at 10 r/min, 20 r/min, 30 r/min were selected. Since the feasible range of helix angle: 0° to 60° and opening 0 mm to 60 mm, the helix angles were set into 0° (straight grooved wheel), 25° and 50°, and the openings were 20 mm, 40 mm and 60 mm. The fertilizer adopted in this experiment was MCT.

L9(34) meter was used in this test. Using the continuous grid measurement method (described in section 2.2.1), the variation coefficient of fertilizer quality in each grid were calculated as shown in Table 3 and Figure 6.

According to Table 3 that the R values of three factors is greater than the R_e value at low speed (10-30 r/min), and the three factors have influence on the fertilization uniformity and the effects of these factors are interactive. it can also be seen that helix angle has the greatest influence and Group 9 has the best uniformity with the helix angle of 50°, the rotational speed of 30 r/min, and the opening of 40 mm.

The results show that the helix angle is the main factor affecting the fertilization uniformity. Designing the fluted roller into a spiral fluted roller is conducive to improving the fertilization uniformity of fertilizer applicators. Thus, it is necessary to study the selection of helix angle. Meanwhile, since rotational speed of the fluted roller also has a great impact on the fertilization uniformity, it needs to be comprehensively considered in the study.

Table 3 Results of orthogonal test

Test number	Factor				Variation coefficient
	Helix angle/(°)	Rotational speed/r·min^{-1}	Opening/mm	Error/%	
1	0	10	20	1	52.0%
2	0	20	40	2	30.0%
3	0	30	60	3	12.1%
4	25	10	40	3	16.0%
5	25	20	60	1	6.3%
6	25	30	20	2	9.3%
7	50	10	60	2	8.8%
8	50	20	20	3	7.9%
9	50	30	40	1	4.4%
K_1	0.31	0.26	0.23	0.21	
K_2	0.11	0.15	0.17	0.16	
K_3	0.07	0.09	0.09	0.12	
R	0.24	0.17	0.14	0.09	

Note: The importance order of the influencing factors are: helix angle>rotational speed>opening of fluted roller. The second orthogonal test showed that the importance order of the factors affecting the fertilization accuracy are: installation angle>rotational speed>helix angle of fluted roller.

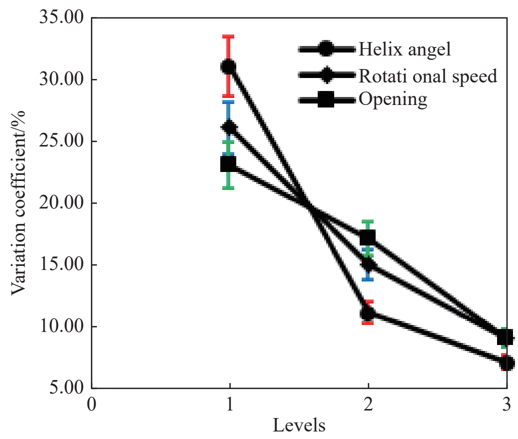


Figure 6 Variation coefficient of factor levels

4.2 Orthogonal test on the accuracy of fertilizer discharge

The design of an ideal spiral fluted roller needs to solve the problem of low fertilization accuracy of fertilizer discharge is not high under the different openings, that is, the linear relationship between opening and fertilizing amount is not strong. It was found by the existing studies[21,25] that it is hard to maintain the fertilization accuracy when the spiral fluted roller is applied to the traditional fertilizer applicators with horizontal installed fluted roller (the installation angle is 0°).

To study the fertilization accuracy under opening control, the correlation coefficient square R^2 between fertilizing amount and opening and the regression intercept a in the fitting equation are regarded as the evaluation index. In order to confirm the main factors that affect the correlation coefficient square of opening and fertilizing amount R^2, this test studied the influence of installation angle, rotational speed and helix angle of the fluted roller on the fertilization accuracy under opening regulation (Table 4). Since the maximum value of installation angle is 60°, the installation angles were set into 0° (traditional horizontal installed fluted roller), 30° and 60°. The fertilizer selected in this test is MCT.

The fertilizing amount was measured in 5 s by the method mentioned in section 2.2.2, and the data was recorded using L9 (34) meter. Taking the opening of 10 mm, 20 mm, 30 mm, 40 mm and 50 mm in turn, the correlation coefficient square R^2 between fertilizing amount and opening of each group is given in Table 5. It can be noticed that the R values of three factors are greater than the R_e value, which indicate that the three factors have an impact on the fertilization accuracy under different openings, and among them, installation angle has the most obvious effect, and then the rotational speed and opening are in turn. The results also illustrate the interactive effects of the three factors, and Group 8 has the best uniformity with the rotational speed of 50 r/min, the installation angle of 30° and the helix angle of 0°.

Table 4 Selection of test factor level in orthogonal test

Level	Rotational speed/r·min^{-1}	Installation angle/(°)	Helix angle/(°)
1	16.6	0	0
2	33.3	30	25
3	50.0	60	50

Table 5 Results of orthogonal test

Test number	Factor				Variationcoefficient
	Rotational speed/r·min^{-1}	Installation angle/(°)	Helix angle/(°)	Error/%	
1	16.6	0	0	1	0.9712
2	16.6	30	25	2	0.9935
3	16.6	60	50	3	0.9943
4	33.3	0	25	3	0.9485
5	33.3	30	50	1	0.9889
6	33.3	60	0	2	0.9873
7	50	0	50	2	0.9388
8	50	30	0	3	0.9973
9	50	60	25	1	0.9915
K_1	0.9863	0.9528	0.9853	0.9839	
K_2	0.9749	0.9932	0.9778	0.9732	
K_3	0.9759	0.9910	0.9740	0.9800	
R	0.0114	0.0404	0.0113	0.0107	

Note: The importance order of the factors affecting the fertilization accuracy are: installation angle>rotational speed>helix angle of fluted roller.

The experimental results show that installation angle is the main factor affecting the fertilization accuracy under different openings. Designing the fluted roller into a vertical installed fluted roller will benefit to improve the fertilization accuracy under opening regulation. At the same time, the results indicate that it is necessary to further study the selection of installation angle.

5 Performance test and analysis

5.1 Test on helix angle and fertilizing performance

According to the above results of two orthogonal experiments, this section focuses on the influence of helix angle on fertilization uniformity, and comprehensively consider the influence of rotational speed on the uniformity and accuracy of fertilizer discharge. Based on the continuous grid method (mentioned in section 2.2.1), the fluted rollers with helix angle of 0°, 15°, 30°, 45° and 60° are selected, and the opening is constant at 30 mm. The rotational speeds of fluted rollers are 0 r/min, 20 r/min, 30 r/min, 40 r/min and 50 r/min, respectively. The variation coefficients of fertilizing amount are given in Table 6, and the total amount of fertilizer in 20 boxes is provided in Table 7. Three kinds of fertilizers, Lardmee, Cnampgc and MCT, were used in this test.

The results given in Table 6 were analyzed by variance of two factor random block. Different kinds of fertilizers were regarded as different regional groups. Duncan method was used for posttest. The F values of rotational speed, helix angle and fertilizer types are 5.351, 12.773 and 0.158, respectively, and the corresponding significances are 0.00, 0.00 and 0.854, respectively. The rotational speed and helix angle have significant impact on the fertilization uniformity, while the type of fertilizer has no significant impact. The significance value is less than 0.01, indicating that the influence of factors on the test results is extremely significant; The significance value is less than 0.05, indicating that the factors have a significant impact on the test results; The significance value is greater than 0.05, indicating that the factors have no significant influence on the test results.

Table 6 Variation coefficients of grid fertilizer quantity under different helix angles and rotational speeds

Rotational speed/r·min^{-1}	Helix angle (Lardmee)				
	0°	15°	30°	45°	60°
10	52.50%	40.00%	32.60%	14.70%	12.50%
20	32.60%	24.10%	9.30%	7.90%	7.40%
30	11.10%	9.40%	5.20%	4.60%	5.20%
40	4.50%	4.80%	4.00%	4.90%	4.30%
50	5.10%	4.70%	4.10%	4.20%	4.00%
Rotational speed	Helix angle (Cnampgc)				
	0°	15°	30°	45°	60°
10	48.90%	44.10%	20.40%	13.10%	12.50%
20	27.80%	22.20%	9.60%	7.30%	7.30%
30	11.20%	8.60%	5.50%	5.40%	5.10%
40	5.30%	5.30%	4.40%	5.00%	4.30%
50	5.70%	4.60%	4.10%	6.70%	3.50%
Rotational speed	Helix angle (MCT)				
	0°	15°	30°	45°	60°
10	51.00%	36.80%	17.70%	13.60%	11.90%
20	28.90%	22.60%	9.50%	8.40%	7.40%
30	11.70%	7.70%	4.30%	4.60%	5.60%
40	4.20%	4.30%	4.00%	4.70%	5.50%
50	6.10%	4.60%	3.30%	4.70%	4.70%

Table 7 Total grid fertilizer quantity in 20 grids under different helix angles and rotational speeds

Rotational speed/r·min^{-1}	Helix angles (Lardmee)				
	0°	15°	30°	45°	60°
10	31.644	30.311	29.467	29.422	27.956
20	59.489	58.578	58.156	56.911	57.956
30	90.667	87.756	89.378	87.067	86.822
40	120.067	121.533	119.489	116.556	114.244
50	152.622	147.578	150.378	144.467	144.289
Rotational speed/r·min^{-1}	Helix angle (Cnampgc)				
	0°	15°	30°	45°	60°
10	28.911	27.111	27.333	27.578	27.822
20	58.756	54.711	54.200	55.022	56.689
30	84.622	85.178	81.911	81.422	80.311
40	113.622	111.178	108.200	107.933	104.244
50	142.133	139.711	136.889	135.733	131.311
Rotational speed/r·min^{-1}	Helix angle (MCT)				
	0°	15°	30°	45°	60°
10	28.622	27.778	28.533	27.667	26.400
20	58.378	55.867	58.578	55.200	55.378
30	86.778	86.267	86.222	83.244	82.378
40	114.400	113.556	116.600	112.222	110.356
50	143.400	139.156	143.444	136.911	136.467

The post-test was conducted based on Duncan method as results provided in Table 8.

Table 8 Homogeneous subset of variation coefficients of grid fertilizer quantity

Rotational speed/ r·min⁻¹	Sample size	subset 1	subset 2	subset 3	Helix angle/(°)	Sample size	subset 1	subset 2
40	15	4.63%			60	15	6.74%	
50	15	4.67%			45	15	7.32%	
30	15	7.01%			30	15	9.20%	
20	15		15.48%		15	15		16.25%
10	15			28.15%	0	15		20.44%
Significance		0.355	1.000	1.000	Significance		0.340	1.000

From the aspect of rotational speed, the variation coefficients of grid fertilizer quality at 30 r/min, 40 r/min and 50 r/min are in subset 1, in which the differences are not obvious, while another two subsets with at the variation coefficients of 10 r/min and 20 r/min are obvious. The best effect of fertilizer uniformity is rotational speed of 40 r/min, and the average variation coefficient of grid fertilizer quality is 4.63%.

From the aspect of helix angle, the variation coefficients of grid fertilizer quality with the helix angle of 30°, 45° and 60° are in subset 1, in which the differences are not obvious. The variation coefficients of grid fertilizer quality with the helix angle of 0° and 15° are in subset 2, that have significant difference. The best effect of fertilizer uniformity is the helix angle of 60° and the average value of variation coefficient of grid fertilizer quality is 6.74%. The above results show that the fertilization uniformity is at a better level when the rotating speed is 30-50 r/min and the helix angle is 30°-60°. The variation coefficient of the fertilization uniformity is less than 9.20%, which meets the criteria on the variation coefficient (less than 40%) in NY/T1003-2006 "Quality Evaluation Specification for Fertilization Machinery".

In Table 8, the linear relationship between fertilizing amount and rotational speed was analyzed. The correlation analysis was carried out in the spiral fluted rollers under five different structural parameters by using three kinds of fertilizers, and the correlation coefficients square R^2 of each case were calculated in Table 9.

Table 9 Fertilizing amount within 5 s under different openings and helix angles

Opening/mm	Helix angle (Lardmee)/(°) 15°	30°	35°	40°	45°	60°
10	50.7	32.2	26.1	31.3	23.0	15.0
20	129.5	81.7	75.4	70.5	70.3	58.6
30	165.9	117.0	109.6	108.1	104.8	91.3
40	193.6	147.4	141.5	143.2	135.1	120.0
50	202.1	173.8	171.3	171.1	164.6	147.7
Opening/mm	Helix angle (Cnampgc) 15°	30°	35°	40°	45°	60°
10	38.6	22.9	23.9	26.2	19.0	12.7
20	103.1	70.2	65.1	64.5	59.2	48.5
30	137.5	101.1	95.3	95.4	89.1	77.0
40	163.3	129.7	122.4	124.3	117.5	103.7
50	179.8	156.0	150.0	150.6	144.9	130.0
Opening/mm	Helix angle (MCT) 15°	30°	35°	40°	45°	60°
10	49.9	32.4	30.6	29.9	23.6	17.2
20	118.4	82.2	74.9	71.7	67.3	54.3
30	153.0	116.1	108.3	104.6	98.8	85.4
40	179.3	146.2	139.1	135.6	129.4	114.3
50	190.5	173.6	167.9	164.4	155.5	135.7

As the structure of spiral fluted rollers influences the filling of fertilizer to some extent, it results in a slight change in the filling coefficient ψ at different rotational speeds, and further affects the accuracy of fertilizing amount. According to table 8, when the helix angle is 0° and 45°, the strong linear relationship can be found between fertilizing amount and rotational speed. According to the variation coefficient of fertilizer quality in each grid and the correlation coefficient square R^2 between fertilizing amount and rotational speed, the spiral angle can be set to 45° to achieve ideal uniformity and accuracy of fertilizer discharge. When the helix angle was 45°, the variation coefficient of fertilization uniformity was 4.20%-14.70%. Much smaller than the variation coefficient of the current fertilization machinery of 28.25%[25].

5.2 Test on installation angle and fertilizing performance

In this section, the influence of installation angle on the fertilization accuracy under different openings was studied, and the spiral fluted roller was set to be the optimal spiral angle of 45° according to the experimental results obtained in Section 4.1.

Through the orthogonal test in section 3.2, when the installation angle is 0°, the correlation coefficient square R^2 between opening and fertilizing amount is low, which means the accuracy of fertilizing amount is poor. The installation angles were initially selected as 15°, 30°, 45° and 60°, and two levels of 35° and 40° were supplemented according to the preliminary test results. During the test, the openings of the spiral fluted roller were taken as 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm in turn.

The fertilizing amount was measured when the fertilizer applicator operates for 5 s at each installation angle as seen in Table 9. When the opening is 0 mm, it is regarded as 0 g of fertilizer discharge, andthe regression equation was fitted for the relationship between opening and fertilizing amount at each installation angle as shown in Figure 7, and the correlation coefficients square R^2 were calculated. Three kinds of fertilizers, Lardmee, Cnampgc and MCT, were used in this test.

5.3 Discussion

The absolute value of the regression intercept a and the correlation coefficient square R^2 in the regression equation in Table 10 were analyzed by two groups of two-factor variance analysis, in which the factors were fertilizer type and installation angle. Duncan method was used for posttest.

Table 10 Regression equation and R^2 under different installation angles

Fertilizer	Installation angle/(°)	Regression equation	R^2
Lardmee	15	$y = 4.2165x + 18.249$	0.9292
	30	$y = 3.5716x + 2.7267$	0.9905
	35	$y = 3.5335x – 1.0371$	0.9935
	40	$y = 3.5109x – 0.4114$	0.9978
	45	$y = 3.4113x – 2.3114$	0.9933
	60	$y = 3.1029x – 5.4829$	0.9904
Cnampgc	15	$y = 3.7349x + 10.344$	0.9585
Cnampgc	30	$y = 3.2318x – 0.821$	0.9910
	35	$y = 3.0737x – 0.7248$	0.9952
	40	$y = 3.0806x – 0.179$	0.9969
	45	$y = 2.9991x – 3.3638$	0.9946
	60	$y = 2.7182x – 5.9724$	0.9915
MCT	15	$y = 3.9287x + 16.965$	0.9396
	30	$y = 3.5517x + 2.9571$	0.9907
MCT	35	$y = 3.4237x + 1.2019$	0.9955
	40	$y = 3.3481x + 0.6705$	0.9968
	45	$y = 3.2179x – 1.3486$	0.9942
	60	$y = 2.8592x – 3.660$	0.9924

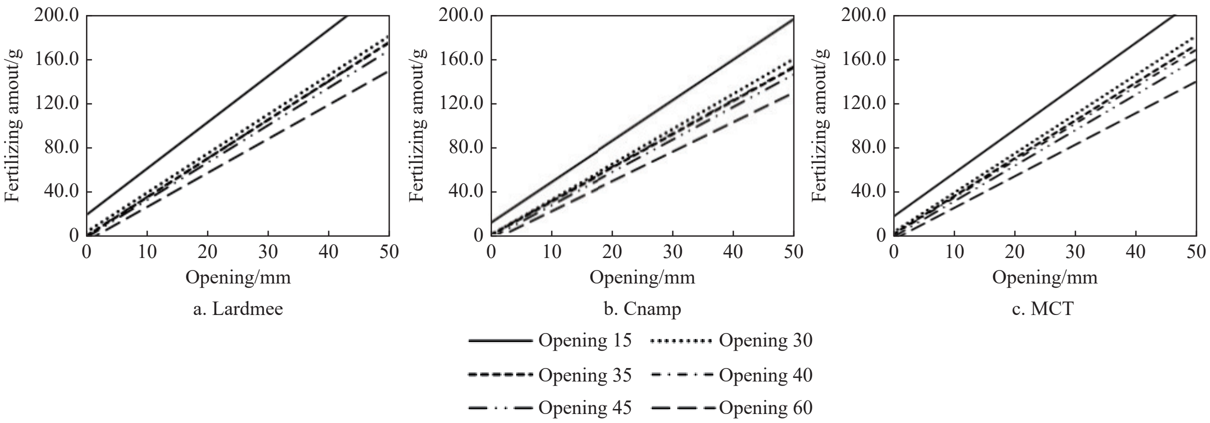


Figure 7 Fitting lines of relationship between fertilizing amount and opening

The *F* values of installation angle and fertilizer type are 24.661 and 0.879, respectively, and the significance values are 0.00 and 0.445, respectively. Installation angle has significant influence on the regression intercept *a* of the regression equation for opening and fertilizing amount, while different fertilizers have no significant influence on it.

From the test and analysis of the intersubjective effect on the correlation coefficient square R^2, the *F* values of installation angle and fertilizer type are 37.251 and 1.281 respectively, and the significance values are 0.00 and 0.320 respectively. It indicates that installation angle has a significant effect on the correlation coefficient square R^2 between opening and fertilizing amount, while different fertilizers have no significant effect on it. The post test was conducted based on Duncan method and the results are given in Table 11.

The regression intercept *a* of the regression equation with the installation angles of 30°, 35°, 40° and 45° was analyzed. The other two subsets were installation angles of 15° and 60°, and the variation coefficients of fertilizer quality in each grid were significantly different under different subsets. The regression intercept *a* is the closest to 0 when the installation angle is 40° and the average value of regression intercept *a* is 0.4023.

The correlation coefficient square R^2 between opening and fertilizing amount under the installation angle of 30°, 35°, 40°, 45° and 60° were set as subset 1, and the difference was not obvious. The correlation coefficient square R^2 with installation angle of 15° was subset 2. There are differences in the fertilization uniformity between the two subsets. The best value of R^2 is 0.9971, when the installation angle is 40°.

Table 11 Homogeneous subset of correlation coefficient square R^2 and regression intercept *a*

Installation angle/(°)	Sample size	Subset 1	Subset 2	Subset 3	Installation angle/(°)	Sample size	Subset 1	Subset 2
40	3	0.402 33			40	3	0.9971	
35	3	0.9893			35	3	0.9947	
30	3	2.1683	2.1683		45	3	0.9940	
45	3	2.3413	2.3413		60	3	0.9914	
60	3		5.0383		30	3	0.9907	
15	3			15.186	15	3		0.9424
Significance		0.283	0.113	1.000	Significance		0.251	1.000

The above results indicate that the small installation angle (e.g., 0°, 15°) leads to weak linear relationship between opening and fertilizing amount, and low fertilization accuracy under different openings, which is not conducive to precision fertilization. Considering both the correlation coefficient square R^2 and regression intercept *a* in Figures 8 and 9, the fertilization accuracy is acceptable when the installation angle is 30°, 35°, 40° or 45°, and these two indexes are the optimal when the installation angle is 40°. Therefore, the installation angle of spiral fluted roller is determined as 40°.

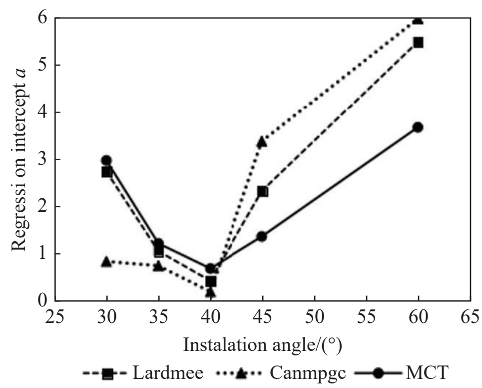


Figure 8 Fitting lines of regression intercepts a and installation angles

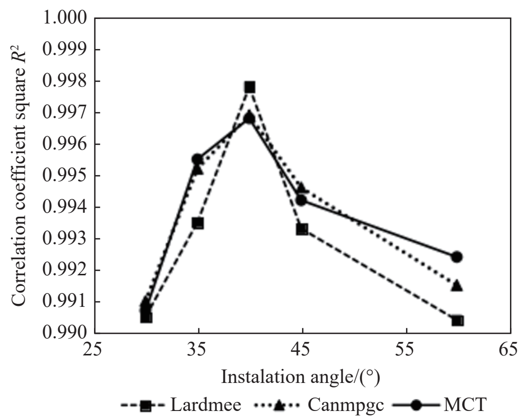


Figure 9 Fitting lines of correlation coefficients square R^2 and installation angles

6 Conclusions

In this study, the design of fertilizer applicator with spiral fluted roller is improved to enhance the uniformity and accuracy of fertilizer discharge.

In the experimental test, the variation coefficient of fertilizing amount within 0.2 s is set as the index to evaluate the fertilization uniformity, and the first-order linear correlation coefficient square R^2 between control variable (rotational speed or opening) and fertilizing amount is used to measure the accuracy of fertilizer discharge. The first orthogonal test proved that influencing factors on the uniformity in order of their importance are: helix angle, rotational speed, and opening. The second orthogonal test showed that the influencing factors affecting the accuracy in order of their importance are: installation angle, rotational speed, and helix angle. Based on these findings, the helix angle and the installation angle of spiral fluted roller were optimized to improve the fertilizing performance.

Though experimental tests the optimized helix angle and installation angle are determined to be 45° and 40°, respectively. Compared with the traditional fertilizer applicator with horizontal installed straight fluted roller, the variation coefficient of fertilizing amount within 0.2 s at low speed (10-30 r/min) is reduced from 5.1%-52.5% to 4.2%-14.7%, and the correlation coefficient square R^2 between fertilizing amount and opening is increased from 0.93-0.97 to no less than 0.996, and the regression intercept in the fitting equation is reduced from larger than 10.0 to less than 1.0. It should be noted that the optimization effect can be also applied on the operation process of other granular fertilizers with particle diameter less than 5 mm.

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