DESIGN AND TEST OF QUANTITATIVE FERTILIZER FEEDING DEVICE FOR POINT-APPLIED FERTILIZATION DEVICE
/
穴施肥装置精量供肥器设计与试验

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ABSTRACT
To ensure accurate and consistent fertilizer application, the key component of the fertilizer feeding device, the grooved wheel, was designed and theoretically analyzed, and the number of grooves of the fertilizer wheel was determined to be 9. The effects of grooves inclination angle, grooves length and operating speed on the fertilizer feeding performance were analyzed by single-factor tests, and the appropriate range of factors was determined. The effect of the interaction between groove length and operating speed on the amount of fertilizer discharged from the groove was investigated by a full factorial test, and a quadratic regression was fitted to the test results to establish the regression equations of groove length and operating speed on the average fertilizer application per groove and the coefficient of variation of the average fertilizer application per groove, which can be used to predict the average fertilizer application per groove and the coefficient of variation of the average fertilizer application per groove to solve for groove length and operating speed.

摘要
为保证穴施肥的施肥量准确、一致，本研究对供肥器中的关键零部件供肥轮进行了设计和理论分析，确定了供肥轮槽数为 9。通过单因素试验分别分析了槽孔倾角、槽孔长度和作业速度对供肥性能的影响，并确定了合适的因素范围。通过全因子试验研究了槽孔长度和供肥轮转速间交互影响对穴排肥量的影响，对试验结果进行二次回归拟合，建立槽孔长度和供肥轮转速对每穴平均施肥量和每穴平均施肥量变异系数的回归方程，可以使用该公式预测给定每穴平均施肥量和每穴平均施肥量变异系数求解槽孔长度和供肥轮转速。

INTRODUCTION
Fertilizer application is an effective way to improve soil fertility and increase crop yields (*Cisternas et al.*, *2020*), and the continuous application of chemical fertilizers has led to high and stable grain yields over the years, ensuring food security in China (*Shemi et al.*, *2021*). It was found that cavity application of fertilizer to the root zone of plants can greatly improve fertilizer utilization (*Adu-Gyamfi et al.*, *2019*), and for this reason, a wide range of researchers have developed a cavity fertilizer discharger suitable for mechanized operation (*Du et al.*, 2023a; *Du et al.*, *2022*). Fertilizer feeding device are needed to ensure that the amount of fertilizer applied to the root zone of the plant in the cavity is precise and consistent (*Ma et al.*, *2022*).

The fertilizer feeding device is mainly in the form of external grooved wheel structure (*Jafari*, *1991*), and according to the shape and direction of the groove teeth, the external grooved wheel fertilizer feeder can be divided into straight groove, oblique groove and spiral groove, etc. (*Kara et al.*, *2010*; *Nukeshev et al.*, *2017*). The straight groove fertilizer feeding device is simple in structure and easy to adjust the discharge volume, *Ding et al.,* (*2018*), used a straight groove feeding device to supply a continuous stream of fertilizer granules when applying fertilizer in layers. Although the structure of the oblique groove fertilizer feeding device is more complicated, it can effectively reduce the coefficient of variation of fertilizer supply and is more widely used (*Bangura et al.*, *2020*). The spiral groove fertilizer feeding device has the most complicated structure, and the fertilizer supply can only be adjusted by controlling the speed of the grooved wheel, but it supplies the highest uniformity of fertilizer flow (*Zheng et al.*, *2020*; *Gao et al.*, *2022*; *Sun et al.*, *2020*). In addition, there are some peg-tooth fertilizer feeding devices (*BoydasTurgut*, *2007*; *Sugirbay et al.*, *2020*; *Kim et al.*, *2008*), which are more complex in structure and difficult to machine.

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This study takes the straight groove fertilizer feeding device as the research object, and adjusts the transmission ratio and initial installation angle between the feeding device and the point-applied application fertilizer discharging device from the transmission system, so that the grooved holes of the fertilizer wheel correspond to the chambers of the fertilizer discharging wheel one by one, thus achieving the consistency of fertilizer discharge per cavity. The discrete element simulation software EDEM was used to optimize and analyze the fertilizer supply performance to ensure the accurate and consistent fertilizer volume of point-applied application, in order to provide a theoretical basis for the promotion and application of fertilizer point-applied application technology.

MATERIALS AND METHODS
STRUCTURE AND KEY PARAMETERS

The structure of fertilizer feeder is shown in Figure 1, which consists of brush, grooved wheel, shell, fertilizer outlet and fertilizer supply pipe. When working, fertilizer particles fill the space above the grooved wheel, and when the wheel rotates, some fertilizer particles fill the grooved hole under the action of gravity and pressure of fertilizer layer above, and then the excess fertilizer particles above the grooved hole are removed under the action of brush, and then the fertilizer particles in the grooved hole are poured out by rotating to the unloading area, and enter the fertilizer supply pipe through the fertilizer outlet.

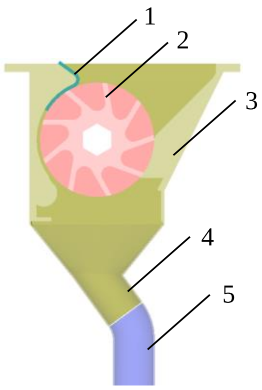

Fig. 1 – Structure of fertilizer feeding device

1. brush; 2. grooved wheel; 3. shell; 4. fertilizer outlet; 5. fertilizer supply pipe

According to GB/T 37088-2018 technical guide for one-time fertilization of corn, 58.33-66.67 kg/667 m^2 of slow-release compound fertilizer with N-P_2O_5-K_2O 24-6-10 needs to be applied, and the amount of fertilizer applied per point is calculated to be 9.84-11.25 g with a bulk density of fertilizer particles of 1.08 g/cm^3 at a maize row spacing of 60 cm×25 cm. The volume of fertilizer granules per point is 9.11-10.42 cm^3, and the grooved wheel per groove is 2.5-15 g, which corresponds to 14.815-88.890 kg/667 m^2, which can basically meet the fertilization requirements of most crops. When the fertilizer application rate is 2.5-15 g per groove, the length of the grooved hole of the fertilizer wheel is 10-60 mm, and the cross-sectional area of the corresponding grooved hole is 231.48 mm^2. The diameter of the fertilizer wheel is 67.5 mm, and the thickness of the grooved hole spacer is 3 mm.

To determine the cross-sectional structural dimensions of a grooved hole, a single grooved hole is considered to be composed of several parts, as shown in Figure 2.

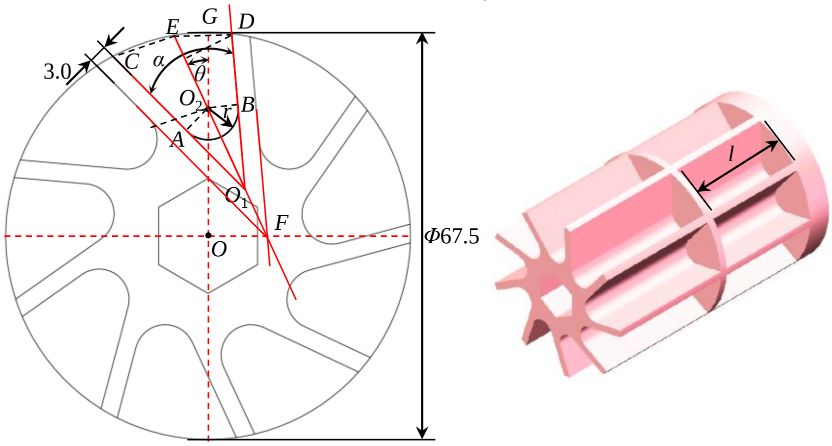

Fig. 2 – Structure of fertilizer grooved wheel

To calculate the cross-sectional area of the grooved hole, the grooved hole cross-section *ABDC* is considered as the difference between the sum of the areas of the two triangles CEO_1 and EDO_1 and the area of the curved surface ABO_1, where:

$$S_{ABO_1} = S_{AO_1BO_2} - S_{ABO_2} = \frac{r^2}{\tan\frac{\alpha}{2}} - \frac{\left(180^\circ - \alpha\right)\pi r^2}{360^\circ} \tag{1}$$

From the geometric relationship, it is known that:

$$\frac{O_1O_2}{FO_2} = \frac{BO_2}{BO_2+3} \Rightarrow FO_2 = \frac{O_1O_2\left(BO_2+3\right)}{BO_2} = \frac{r+3}{\sin\frac{\alpha}{2}} \tag{2}$$

In the triangle OO_2F:

$$OO_2 = FO_2\cos\theta = \frac{\left(r+3\right)\cos\theta}{\sin\frac{\alpha}{2}} \tag{3}$$

Therefore, for the line *OG:*

$$GO_2 = GO - OO_2 = \frac{67.5}{2} - \frac{\left(r+3\right)\cos\theta}{\sin\frac{\alpha}{2}} \tag{4}$$

Since triangles EGO_2 and OFO_2 are similar triangles:

$$\frac{EO_2}{FO_2} = \frac{GO_2}{OO_2} \Rightarrow EO_2 = \frac{GO_2 \times FO_2}{OO_2} = \frac{67.5}{2\cos\theta} - \frac{r+3}{\sin\frac{\alpha}{2}} \tag{5}$$

Therefore, it is possible to obtain:

$$S_{CEO_1} = CO_1 \times \frac{EO_1 \times AO_2}{O_1O_2} = CO_1 \times \frac{\left(EO_2 + O_1O_2\right)r}{O_1O_2} = CO_1 \times \left(\frac{67.5\sin\frac{\alpha}{2}}{2\cos\theta} - 3\right) \tag{6}$$

Similarly, it can be obtained:

$$S_{EDO_1} = EO_1 \times \frac{EO_1 \times AO_2}{O_1O_2} \tag{7}$$

After sorting, the following is obtained:

$$S_{ABDC} = S_{CEO_1} + S_{EDO_1} - S_{ABO_1} \tag{8}$$

According to equation (8), the relationship between the inclination angle θ and the cross-sectional area S of the grooved holes is shown in Figure 3 for the number of grooved holes 8 and 9.

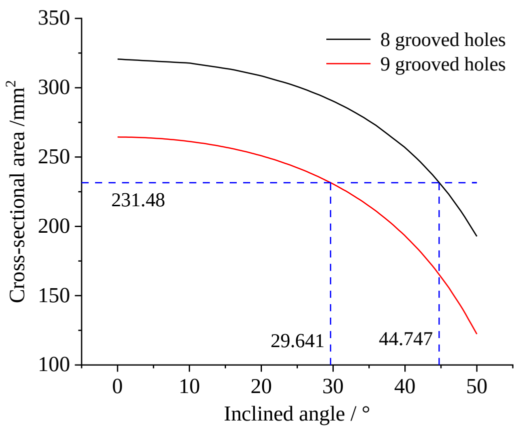

Fig. 3 – Relationship between the number of grooved holes and the inclined angle of the grooved holes on the cross-sectional area of the grooved holes

From the figure, it can be seen that when the number of grooved holes is 8, the grooved hole inclination angle θ is 44.747° and the grooved hole cross-sectional area S is 231.48 mm^2; when the number of grooved holes is 9, the grooved hole inclined angle θ is 29.641° and the grooved hole cross-sectional area S is 231.48 mm^2. When the number of grooved holes is 10, the inclined angle θ of the grooved holes is less than 231.48 mm^2, so the graph is not analyzed; the situation when the number of grooved holes is 7 is also not analyzed, because the smaller the number of grooved holes, the larger the increase in the speed of the grooved wheel when the operating speed is increased, and the grooved wheel filling performance will be significantly reduced. In order to improve the fertilizer filling performance of the grooved wheel, the number of grooved holes of the wheel is set to 9, and the grooved hole tension angle is 40°, and the grooved hole inclined angle is decided according to the simulation test later.

Simulation model construction

To investigate the mechanism of the influence of the above factors on the fertilizer application amount per point, the discrete element simulation software EDEM2020 was used to simulate the grooved wheel filling and fertilizer application process in order to optimize the best structural parameters. The fertilizer feeding device was modeled using SolidWorks 2016, saved in .step format, and imported into EDEM2020, as shown in Figure 4. The total simulation time was 10 s, and the data was saved every 0.01 s.

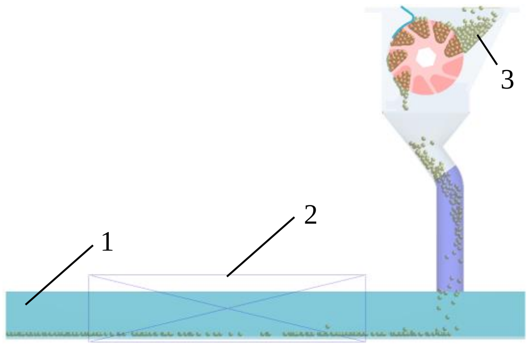

Fig. 4 – Modeling and simulation diagram of fertilizer feeding device

1. Conveyor belt; 2. Geometry bin; 3. Fertilizer granules

The EDEM simulation model of fertilizer granules was established by using Bekosh coated controlled release fertilizer (N-P_2O_5-K_2O 24-6-10) produced by Shandong Nongye Biotechnology Co. The intrinsic parameters and contact parameters used in the simulation are shown in Table 1 (*Du et al.*, *2023b*; *Du et al.*, *2022*).

Table 1

Simulation parameters table

Parameters	Fertilizer granules	ABS	Conveyor belt
Poisson's ratio	0.225	0.394	0.3
True Density (kg/m^3)	2474	1060	2500
Shear modulus (Pa)	1.528×10^8	8.9×10^8	1.0×10^6
Coefficient of restitution	0.509	0.475	0.02
Coefficient of static friction	0.176	0.425	1.25
Coefficient of rolling friction	0.0332	0.0951	1.24

Test indicators

To evaluate the performance of the grooved wheel, select Add Selection in the Setup Selections sub-panel of the EDEM post-processing and add a Geometry bin, adjusting its position so that it is on the upper left side of the conveyor belt, with a length of 250 mm (i.e., the amount of fertilizer required for one corn plant), and a width and height of 80 mm and 60 mm, respectively, so that the length is set to 250 mm (i.e., the amount of fertilizer needed for one corn plant), and the width and height are set to 80 mm and 60 mm, respectively, to cover the conveyor belt. To ensure that fertilizer particles are not counted repeatedly when using the Geometry bin, it is necessary to ensure that the product of the time interval between each count and the speed of the conveyor belt (i.e., operating speed) is greater than or equal to 250 mm, and then calculate the average fertilizer application per point (AFA), the coefficient of variation of the average fertilizer application per point (COVAFA), and the error of the average fertilizer application per point (EOAFA) according to the following equations.

$$Q_{average} = \frac{\sum_{i=1}^{k} Q_i}{k} \times 100\% \tag{9}$$

$$C_Q = \frac{\sqrt{\frac{1}{k}\sum_{i=1}^{k}\left(Q_i - Q_{average}\right)^2}}{Q_{average}} \tag{10}$$

$$q = \frac{\sum_{i=1}^{k} \frac{\left|Q_i - Q_0\right|}{Q_0}}{k} \times 100\% \tag{11}$$

Where: $Q_{average}$ is the average fertilizer application per point, g; Q_i is the *i*-th hole fertilizer application, g; *k* is the total number of points counted; C_Q is the coefficient of variation of the average fertilizer application per point; *q* is the error of the average fertilizer application per point, %; Q_0 is the standard fertilizer discharge per point, g.

RESULTS

Effect of grooved hole inclination on the amount of fertilizer applied to the point

The effect of groove inclined angle on the amount of fertilizer applied to the point is shown in Figure 5 for an effective working length of 30 mm, a rotation speed of 40 r/min and groove inclined angles of 20°, 22.5°, 25°, 27.5° and 30°, respectively.

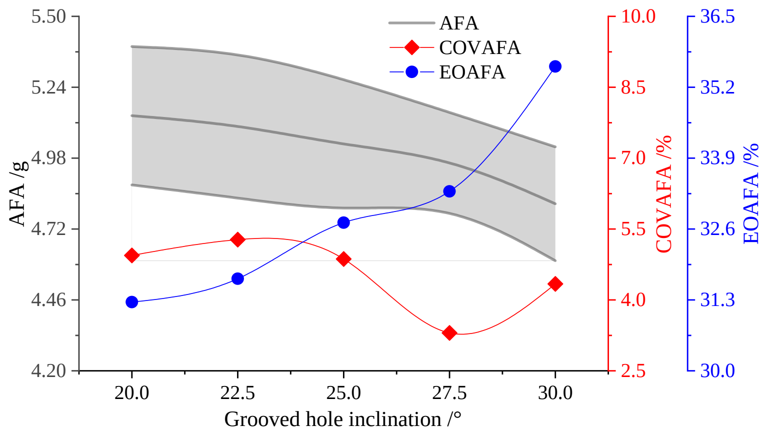

Fig. 5 – Effect of grooved hole inclination on the amount of fertilizer applied to the point

From Figure 5, the AFA gradually decreases when the inclination of the grooved hole gradually increases, probably due to the increase of the grooved hole opening caused by the increase of the inclination angle, although it is easier to fill the fertilizer particles, some particles are found to be easily cleared out of the grooved hole when passing through the brush, because the increase of the grooved hole opening leads to more particles above the edge of the grooved hole, and there is a greater probability that the fertilizer particles inside the grooved hole will be taken out of the grooved hole when passing through the brush. Therefore, the AFA is reduced. As the inclination of the grooved hole gradually increases, the EOAFA gradually increases, because the AFA gradually decreases and the difference between the AFA and the theoretical AFA increases. The COVAFA was basically maintained at 3.3%~5.3% when the inclination angle of the grooved hole was 20°~30°, and the COVAFA was the smallest when the inclination angle of the grooved hole was 27.5°, which was 3.3%. From the standard deviation of AFA (shaded area in the figure), it can be seen that the standard deviation is also the smallest when the grooved hole inclination angle is 27.5°.

From the above analysis, it can be seen that the inclination angle of the grooved hole affects the AFA, and then affects the EOAFA, and the coefficient of variation and standard deviation of the average fertilizer application per hole are the smallest when the tilting angle of the grooved hole is 27.5°, so the stability of the AFA can be improved by appropriately reducing the tilting angle of the grooved hole. Therefore, the final selection of grooved hole inclination angle was 27.5°.

Effect of grooved hole length on the amount of fertilizer applied to the point

The effect of grooved length on the amount of fertilizer applied to the point is shown in Figure 6 for an inclination angle of 30°, a rotation speed of 40 r/min, and effective working lengths of 10 mm, 20 mm, 30 mm, 40 mm, and 50 mm, respectively.

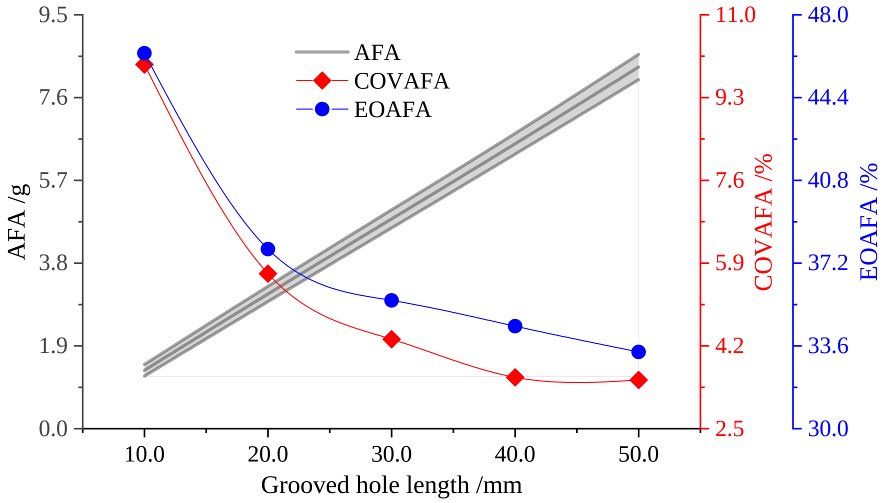

Fig. 6 – Effect of grooved hole length on the amount of fertilizer applied to the point

As shown in the figure 6, when the length of the grooved hole gradually increases, the AFA gradually increases and the EOAFA gradually decreases, because the AFA increases when the length of the grooved hole increases, the opening area of the grooved hole becomes larger, and fertilizer particles can easily fill the grooved hole space, while it is difficult for fertilizer particles to fill the grooved hole when the length of the grooved hole is small, and the difference between the theoretical AFA and the AFA increases, resulting in the COVAFA and the EOAFA being large. When the length of grooved hole was 30 mm~40 mm, the COVAFA was less than 4.3%.

From the above analysis, it can be seen that the length of the grooved hole affects the AFA, and the coefficient of variation and standard deviation of the average fertilizer application per hole are smaller when the grooved hole length is greater than 30 mm, so the stability of the average fertilizer application per hole can be improved by appropriately increasing the grooved hole length.

Effect of operating speed on the amount of fertilizer applied to the point

The effect of the rotation speed of the fertilizer wheel on the amount of fertilizer applied to the point is shown in Figure 7 for an inclination angle of 30°, an effective working length of 30 mm, and rotation speeds of 13.3, 26.7, 40, 53.3, and 66.7 r/min, respectively.

As can be seen from the figure 7, when the speed of the fertilizer supply wheel gradually increases, the AFA gradually decreases, because the fertilizer granule filling time becomes shorter due to the increase in the speed of the fertilizer supply wheel, and it is difficult for the fertilizer granule to fill the grooved hole smoothly. The EOAFA gradually increases when the speed of the fertilizer supply wheel gradually increases, because the AFA gradually decreases and the difference between the AFA and the theoretical fertilizer AFA increases. The COVAFA was 0.4%~7.4% when the speed of the fertilizer wheel was 13.3 r/min~66.7 r/min, and the COVAFA increased sharply at the speed of the fertilizer wheel. From the standard deviation of AFA (shaded area in the figure), it can be seen that the standard deviation gradually increased when the fertilizer supply wheel speed was less than 40.0 r/min, but the standard deviation increased rapidly when the fertilizer supply wheel speed was greater than 40.0 r/min.

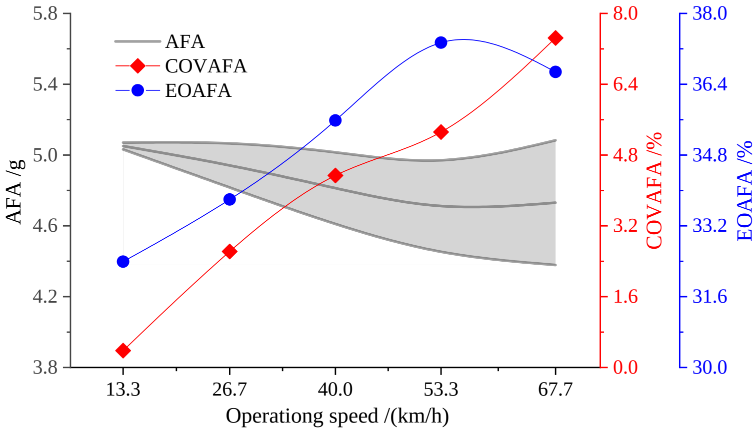

Fig. 7 – Effect of operating speed on the amount of fertilizer applied to the point

From the above analysis, it can be seen that the speed of the fertilizer supply wheel affects the AFA, and then affects the EOAFA, and the coefficient of variation and standard deviation of the average fertilizer application per hole gradually increase when the speed of the fertilizer supply wheel increases.

Modeling the amount of fertilizer applied to the point

Based on the above analysis, the inclination angle of the grooved hole was determined to be 27.5°. In order to study the effect of the interaction between grooved hole length and wheel speed on point discharge, a full factorial test was designed with grooved hole length and fertilizer wheel speed as the study factors, and the COVAFA and AFA were used as the study objectives, and a quadratic regression was fitted to the test results to establish the regression equations of the AFA and the COVAFA were established.

The test scheme and test results are shown in Table 2.

Table 2

Full factorial test program and results

No.	Length *l* / mm	Speed *n* / (r/min)	AFA $Q_{average}$ / g	COVAFA C_Q / %
1	10	13.3	1.513319	7.427964
2	10	26.7	1.385602	7.429568
3	10	40.0	1.33648	9.979386
4	10	53.3	1.284328	13.66198
5	10	66.7	1.296442	14.94868
6	20	13.3	3.286889	2.522676
7	20	26.7	3.204958	3.054150
8	20	40.0	3.097446	5.685218
9	20	53.3	3.076655	6.365773
10	20	66.7	3.093146	9.211046
11	30	13.3	5.050821	0.381679
12	30	26.7	4.945997	2.620881
13	30	40.0	4.812601	4.338091
14	30	53.3	4.681243	5.319122
15	30	66.7	4.730656	7.446586
16	40	13.3	6.805114	1.577270
17	40	26.7	6.765353	3.154584
18	40	40.0	6.528549	3.553546

No.	Length *l* / mm	Speed *n* / (r/min)	AFA $Q_{average}$ / g	COVAFA C_Q / %
19	40	53.3	6.465926	4.341058
20	40	66.7	6.572815	7.111936
21	50	13.3	8.597962	2.115242
22	50	26.7	8.467234	2.886364
23	50	40.0	8.300637	3.499694
24	50	53.3	8.197033	5.255946
25	50	66.7	8.304938	8.007886

A quadratic multiple regression fit to the coefficient of variation of average fertilizer application per hole and average fertilizer application per hole yields the regression equation

$$\begin{aligned} Q_{average} &= -0.0525 + 0.1774l - 0.01539n + 4.066\times10^{-6} l^2 - 6.667\times10^{-5} ln + 0.0001504n^2 \\ C_Q &= 11.05 - 0.6305l + 0.07844n + 0.00909l^2 - 0.001398ln + 0.001065n^2 \end{aligned} \tag{12}$$

Where: $Q_{average}$ is the average fertilizer application per hole, g; C_Q is the coefficient of variation of the average fertilizer application per hole; *l* is the length of the grooved hole, mm; n is the speed of the fertilizer supply wheel, r/min.

The summed variance *SSE*, root mean square *RMSE* and coefficient of determination R^2 of the average fertilizer application rate per hole $Q_{average}$ were 0.04572, 0.04906 and 0.9997, respectively; the summed variance *SSE*, root mean square *RMSE* and coefficient of determination R^2 of the average fertilizer application rate per hole C_Q were 13.9, 0.8555 and 0.955, respectively, indicating that the regression model was significant and it is feasible to use this formula to predict the grooved hole length and fertilizer wheel speed for a given average fertilizer application per hole and the coefficient of variation of average fertilizer application per hole.

The interaction effects of grooved hole length and grooved wheel operating speed on the average fertilizer application per hole and the coefficient of variation of the average fertilizer application per hole are shown in Figure 8.

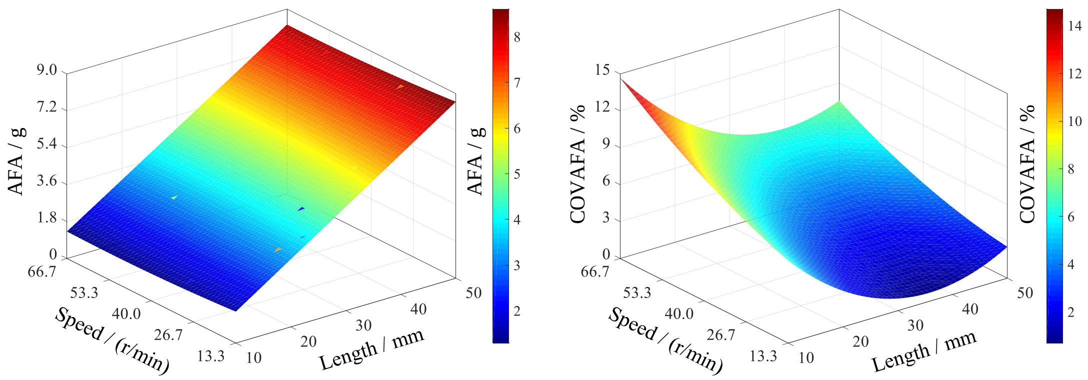

Fig. 8 – Response surface analysis of the interaction effects of factors

CONCLUSIONS

In this study, the key component of the fertilizer feeding device, the grooved wheel, was designed and theoretically analyzed, and the number of grooves of the fertilizer wheel was determined to be 9. The effects of grooves inclination angle, grooves length and operating speed on the fertilizer feeding performance were analyzed by single-factor tests, and the appropriate range of factors was determined. The effect of the interaction between groove length and operating speed on the amount of fertilizer discharged from the groove was investigated by a full factorial test, and a quadratic regression was fitted to the test results to establish the regression equations of groove length and operating speed on the average fertilizer application per groove and the coefficient of variation of the average fertilizer application per groove, which can be used to predict the average fertilizer application per groove and the coefficient of variation of the average fertilizer application per groove to solve the groove length and operating speed.

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