OPTIMIZATION RESEARCH OF FERTILIZER GUIDING MECHANISM BASED ON THE DISCRETE ELEMENT METHOD
/
基于离散元法的导肥装置优化研究

Hong Jian Zhang[1], *Yu Feng* Li[1], *Chun Bao* Xu[1], *Shuang Xi* Liu[1,2], *Ze Kun* Quan[1], *Jin Xing* Wang[*1,2]   [1]
[1] College of Mechanical and Electronic Engineering, Shandong Agricultural University, Taian 271000, China;
[2] Shandong Provincial Key Laboratory of Horticultural Machinery and Equipment, Taian 271000, China;
Tel: +86 05388246826; E-mail: jinxingw@163.com

ABSTRACT

Discrete Element Method was used to study the fertilizer guiding mechanism of double-row orchard ditching fertilizer to solve certain problems, such as the low uniformity of fertilization in orchard. Firstly, on the basis of studying the existing B fertilizer guiding mechanism, A and C fertilizer guiding mechanisms were proposed, and three virtual simulation models of the fertilizer guiding mechanism were established. Secondly, the physical parameters of the fertilizer particles were analysed, combined with the dynamic analysis of the falling process of the fertilizer particles, the dynamic model of the fertilizer particles in the three fertilizer guiding mechanisms was established. Finally, three kinds of fertilizer guiding mechanisms A, B and C were analyzed by the discrete element simulation experiment, and the C fertilizer guiding mechanism was the best. Then, the C fertilizer guiding mechanisms under different curvature radius were simulated, the discrete coefficients of the edge region and the middle region were used to evaluate the fertilizer uniformity, and the optimal curvature radius of the C fertilizer guiding mechanism was obtained. The results of simulation and prototype orchard experiments show that the dispersion coefficients of the edge region and the middle region of the C fertilizer guiding mechanism are the smallest, the uniformity of fertilization is the highest, the A fertilizer guiding mechanism is the second, the B fertilizer guiding mechanism is the lowest; in the C fertilizer guiding mechanism under different radius of curvature, when the radius of curvature is 600mm, the dispersion coefficients of the edge region and the middle region of the C fertilizer guiding mechanism are the smallest, and the fertilization uniformity is the highest; after the optimization, the discrete coefficient is reduced from 0.51 to 0.26, and the fertilization uniformity is increased by 49.02%. This study has significant potential to design and processing of orchard ditching fertilizer applicator.

摘要

针对果园开沟施肥不均匀的问题，采用离散元仿真设计对果园开沟施肥机的导肥机构进行优化。首先，在研究现有 B 型导肥机构基础上，提出 A 型和 C 型导肥机构，建立三种导肥机构的虚拟仿真模型。其次，分析肥料颗粒的物理参数，结合肥料颗粒下落过程中的动力学分析，建立肥料颗粒在三种导肥机构中的动力学模型。最后，先对 A 型、B 型、C 型三种导肥机构进行离散元仿真试验，分析优化出最佳 C 型导肥机构；后对不同曲率半径下的 C 型导肥机构进行施肥均匀度仿真试验，利用边缘区域与中间区域的变异系数评价施肥均匀度，分析优化出 C 型导肥机构的最佳曲率半径。仿真与样机果园试验结果表明：C 型导肥机构边缘区域与中间区域离散系数最小，施肥均匀度最高，A 型导肥机构次之，B 型导肥机构最低；在不同曲率半径的 C 型导肥机构中，曲率半径为 600mm 时，C 型导肥机构边缘区域与中间区域离散系数最小，施肥均匀度最高；优化后变异系数由 0.51 减小到 0.26，施肥均匀度提高 49.02%。为果园开沟施肥机设计加工提供科学依据。

INTRODUCTION

Fertilizer is the food of fruit trees. Fertilization of fruit trees is the key operation link in fruit tree production. The quality of fertilization directly affects the absorption of nutrients in fruit trees. Rational fertilization is the basis for high quality and high yield of fruit trees *(YinYan Shi et al, 2018; XiaoChun Zheng et al, 2011; DaYong Han et al, 2010)*. Fruit trees fertilizers predominantly are inorganic fertilizer and organic fertilizer. Inorganic fertilizer is mainly chemical fertilizer, characterized by strong fertility and fast fertilizer efficiency, but it can easily cause soil structure change, soil organic matter content decline, tree growth and fruit quality reduction.

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[1] *HongJian Zhang, Ph.D. Stud. Eng.; YuFeng Li, M.S. Stud. Eng.; ChunBao Xu, M.S. Stud. Eng.; ShuangXi Liu, As. Ph.D. Eng.; ZeKun Quan, M.S. Stud. Eng.; JinXing Wang, Prof. Ph.D. Eng.*

The application of organic fertilizer can help improve soil physicochemical properties, improve leaf physiology, increase fruit yield and improve fruit quality *(Chen Ma et al, 2017; JuSheng Gao et al,* 2005*; Ning Wu et al, 2016)*. Fertilization uniformity is a key factor affecting the effect of fertilization operations, and it is an important indicator for evaluating the performance and effectiveness of working tools *(Jing Ma et al, 2016; Zhou et al,* 2009*; Ming Li et al, 2016; LiYe Zhao et al, 2002)*. *Patterson et al (1962)* studied the theoretical motion model and motion mechanism of various fertilizer granules, simulated and tested the fertilizer granule distribution and fertilization uniformity, and analysed the average error between the theoretical value and the actual measured value, which laid the foundation for the mathematical theoretical model of the fertilizer application machine. *P. Van Liedekerke et al (2009)* used the discrete element method to start the flow of granules from the container, and the plate and the inclined disk were used to simulate the flow of granules affected by the rotating disk. *Artur Przywara et al (2015)* studied the influence of the structure and operating parameters of the centrifugal disc spreader on the spatial distribution of the fertilizer, determined the rotational speed of the disc, the feed position of the fertilizer on the disc, the blade angle on the disc and the type of fertilizer had affected the spatial distribution of the fertilizer. *Villette et al (2010)* proposed a new method for simultaneously measuring the horizontal flow and vertical flow distribution of a disc-type fertilizer, paving the way for studying the distribution of fertilizer granules and testing the uniformity of fertilization. *Aphale et al (2003)* calculated and tested the trajectories of various fertilizer granules, and obtained the average error between the theoretical value and the actual measured value under different disk rotational speed conditions, which provided a theoretical basis for the test. *Zhang Tao et al (2015)* simulated the fertilization process of the fertilizer-discharging mechanism through discrete elements, formulated design variables and optimization targets, developed motion simulation software and parameterized platform, optimized the structural parameters of the fertilizer-discharging mechanism, and improved the uniformity of fertilization. *Chen Xiongfei et al (2015)* designed a two-stage spiral fertilizer device, and established a mathematical model of the single-circle discharge amount of the fertilizer-fertilizing spiral. It was determined through experiments that the two-stage spiral fertilizer-removing device had better fertilizer-removing effects for various forms and better adaptability with fertilizer. *Yang Xinlun et al (2015)* established the mathematical model of the blade type fertilizer mechanism, formulated the design variables and optimization objectives, developed the motion simulation software and the parameterization platform, and optimized the structural parameters of the blade type fertilizer removal mechanism. *Yuan Wensheng et al (2018)* designed a scoop wheel fertilizer discharge device and established the three-dimensional model for simulation of fertilizer, tested cavitation resistance and uniformity of the amount of fertilizer per entire fertilizer apparatus, and studied the fertilizer discharge effect of the fertilizer discharger under different rotation speeds of the fertilizer components. *Lv Jinqing et al (2015)* carried out simulation tests on the screw-type fertilizer discharge mechanism under different working speed conditions, accurately analysed the mathematical relationship between the rotational speed and the displacement, realized the optimal design of the screw-type fertilizer discharge mechanism, and improved the uniformity of fertilization.

After a comprehensive analysis of research status, and the effect of fertilizer-discharging mechanism on fertilization uniformity, a conclusion was reached that, at present, the research on the effect of fertilizer-dispensing mechanism on fertilization uniformity is mature, but the research on the influence of fertilizer guiding mechanism on fertilization uniformity is still in its infancy. Based on the study of the influence of the fertilizer guiding mechanism on fertilization uniformity, this paper optimizes the existing fertilizer guiding mechanism and provides a theoretical basis for the design and processing of the orchard ditching fertilizer machine.

MATERIALS AND METHODS
Machine Structure

Double-row orchard ditching fertilizer overall structure is shown in Fig.1 and Fig.2, mainly configured by the rack, fertilizer box, transmission, ditching mechanism, fertilizer mechanism, fertilizer guiding mechanism, soil covering machine and the technical parameters of the whole machine are shown in Table 1.

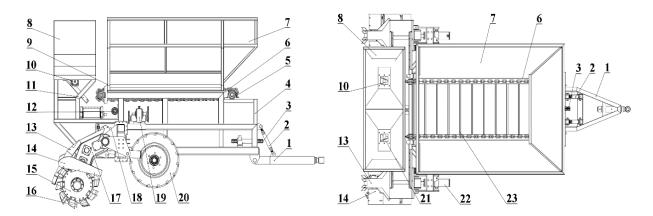| Main technical parameters		Table 1
Item	**Parameters**	**Units**
Supporting power	≥58	Kw
Outline size	3820×2040×2510	mm
Fertilization depth	0~500	mm
Fertilizer application amount	0.5~2	kg.m^{-1}
Base fertilizer application amount	3~5	kg.m^{-1}
Fertilizer box volume	650	L
Base fertilizer box volume	2500	L

Fig. 1 - Main view of the machine   **Fig. 2 - Vertical view of the machine**
1) traction rack; 2) adjusting pull pipe; 3) drive shaft; 4) rack; 5) base fertilizer sprocket; 6) O-chain; 7) base fertilizer box; 8) fertilizer box;
9) base fertilizer outlet; 10) auger; 11) conveyor board; 12) side transmission box; 13) fertilizer guiding mechanism;
14) soil cover; 15) trench cutter disc; 16) trench cutter; 17) trench transmission box; 18) main transmission box;
19) middle transmission box; 20) wheel; 21) fertilizer outlet; 22) hydraulic cylinder; 23) base fertilizer scraper

Fertilizer Guiding Mechanism

The fertilization methods in the orchard mainly include the general application on the whole orchard, the application on the crown, the application on the ring ditch, the application on the strip ditch, the application on the radial ditch and the application in the holes. For new orchards with wide line spacing and wide plant spacing, strip-shaped furrow fertilization is often used. The strip-shaped furrow fertilization method requires strips of 1000~2000mm long, 300~400mm wide and 300~500mm deep between the rows of fruit trees, then fertilize and cover the soil *(Biao Liu et al, 2017; WuZhen Qi et al,* 2019).

Because the amount of fertilization in the orchard is large, in order to ensure the smooth fall of the fertilizer, the fertilizer guiding mechanism of the existing orchard trenching and fertilizing machine is mostly a trough-shaped structure, as shown in Fig. 3. Among them, the fertilizer-in port of the fertilizer guiding mechanism is connected with the fertilizer-out port of the fertilizer-discharging mechanism, and the fertilizer-out port of the fertilizer guiding mechanism is equal to the groove width. The fertilizer plug-in plate in the fertilizer guiding mechanism divides the fertilizer-transfer port and the fertilizer-out port into three parts.
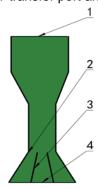

Fig. 3 - Diagrammatic sketch of fertilizer guiding mechanism
1) Fertilizer-in port; 2) Fertilizer-transfer port; 3) Fertilizer plug-in plate; 4) Fertilizer-out port

Parameters Determination of Fertilizer Granules Characteristics

The fertilizer granules used in the experiment were granular organic fertilizers. 100 granular organic fertilizers were randomly selected as the parameter measurement samples, which were placed on blank A4 paper and measured by image processing technology to obtain the accurate size of the granular organic fertilizer.

First, a black square of 10mm×10mm was fabricated on the red A4 paper as an area calibration, and blank A4 paper with area calibration was used as the background plate. Next, the parameter measurement was randomly scattered on the background board, and the original image of granular organic fertilizers was obtained. The colour difference between the test sample and the background plate was used, and a single original image was divided to obtain the threshold value of the other image, as shown in Fig. 4.
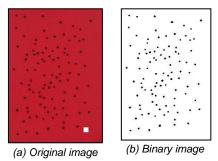
(a) Original image　　　*(b) Binary image*

Fig. 4 - Original image and binary image of granular organic fertilizer

Finally, according to the area calibration on the background plate in the binary image, the equivalent diameter and circularity of the granular organic fertilizer were calculated. Also, the minimum equivalent diameter, the minimum circularity, the maximum equivalent diameter and the maximum circularity, the average equivalent diameter and the average circularity of the statistical parameter measurement sample were calculated, as shown in Table 2.

Table 2

Parameter of granular organic fertilizer

Granular organic fertilizer	Circumference C (mm)	Equivalent diameter $\bar{D}$ (mm)	Circularity $\varnothing$
Average value	9.16	2.92	0.93
Minimum value	7.60	2.42	0.90
Maximum value	11.92	3.79	0.97

It can be seen from Table 2 and Fig. 4 that the circularity of the 100-parameter measurement samples is 0.93, and the concentration is between 0.90 and 0.97. As the circularity of parameter measurement sample gets closer to 1, the closer the parameter measurement sample is to the sphere *(Jin Yuan et al, 2014)*. Since the parameter measurement sample has a high circularity distribution, the granular organic fertilizer is assumed to be spherical during the simulation.

The granular organic fertilizer circularity distribution diagram was drawn, as shown in Fig. 5.

$$Circularity: \varnothing = 4\pi S/C^2 \tag{1}$$
$$Equivalent\ diameter: d = C/\pi \tag{2}$$
$$The\ average\ diameter: \bar{D} = D/N \tag{3}$$
$$D = \sum_{i=1}^{N} d_i \tag{4}$$

In equations (1), (2), (3), (4): S-the area of granular organic fertilizer; C- the circumference of granular organic fertilizer; N-the amount of granular organic fertilizer
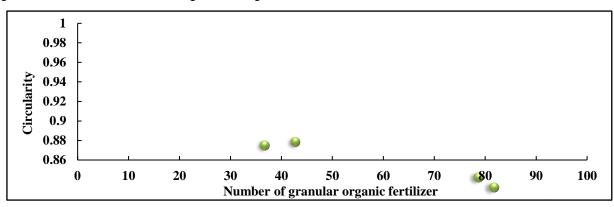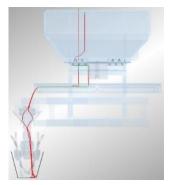

Fig. 5 - Circularity distribution of granular organic fertilizer

The Equation of Motion of Fertilizer Granules in the Fertilizer Guiding Mechanism

Granular organic fertilizers fall into the fertilizer guiding mechanism by means of fertilizer discharge mechanism, with a certain initial velocity v_p. After the granular organic fertilizer enters the fertilizer guiding mechanism, it is subjected to gravity G_p, buoyancy F_{fp}, and air resistance F_{zp}. After the interaction, it finally falls into the ditch of the orchard trenching and fertilizing machine. The specific process is shown in the Fig. 6 *(INNS F.M. et al, 1962)*.
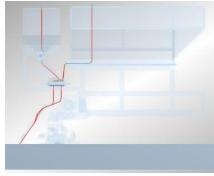
Fig. 6 - Falling process of fertilizer

$$Gravity: \quad G_p = \rho_p V_p \tag{5}$$

$$Buoyancy: \quad F_{fp} = \rho_a V_p g \tag{6}$$

$$Air\ resistance: F_{zp} = \frac{1}{2} K \rho_p S_p V_p^2 \tag{7}$$

$$Air\ resistance\ coefficient: \ K = \frac{3}{8} C_D \rho_a \frac{1}{\rho_p r_p} \tag{8}$$

There is a correlation between drag coefficient C_D and Reynolds number R_e:

$$R_e = 2 \frac{r_p v_p \rho_p}{\eta_a} \tag{9}$$

In equations (5), (6), (7), (8), (9):

ρ_p-granular organic fertilizer density; V_p-volume of granular organic fertilizer; ρ_a-air density;

η_a-aerodynamic viscosity; v_P-granular organic fertilizer velocity;

S_p-granular organic fertilizer frontal area; r_p-granular organic fertilizer radius; g-gravity acceleration;

Assuming that the positive direction of the *Z* axis is opposite to the direction of gravity of the granular organic fertilizer, the equation of motion of the granular organic fertilizer in the *X*, *Y*, and *Z* directions *(Cunningham, F. M, 1963; Pitt, R. E.,1982)* is:

$$X\ direction: \ \frac{d^2 x}{dt^2} = -K v_{Px} \sqrt{v_{Px}^2 + v_{Py}^2 + v_{Pz}^2} \tag{10}$$

$$Y\ direction: \ \frac{d^2 y}{dt^2} = -K v_{Py} \sqrt{v_{Px}^2 + v_{Py}^2 + v_{Pz}^2} \tag{11}$$

$$Z\ direction: \ \frac{d^2 z}{dt^2} = -K v_{Pz} \sqrt{v_{Px}^2 + v_{Py}^2 + v_{Pz}^2} \tag{12}$$

In equations (10), (11), (12):

v_{Px}-the velocity component in the *X* direction;

v_{Py}-the velocity component in the *Y* direction;

v_{Pz}-the velocity component in the *Z* direction;

Fertilization Uniformity Evaluation

The granular organic fertilizer passes through the fertilizer guiding mechanism and finally falls into the ditch of the orchard ditching fertilizing machine. In order to evaluate the uniformity of fertilization, the distribution range of fertilizer in a ditch is selected as the sampling area, and meshing is performed according to 15 rows and 15 columns, as shown in Fig. 7. Among them, the width of the sampling area is the groove width, and the cell grid size is 20mm×20mm.
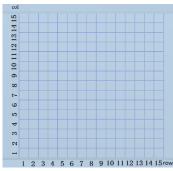

Fig. 7 - Mesh partition of sampling regions

The discrete coefficient CV is used as a measure of the uniformity of fertilizer distribution.
The equations for calculating the discrete coefficient is:

$$CV = \frac{S}{\bar{q}} \tag{13}$$

$$S = \sqrt{\frac{\sum_{i=1}^{n}(q_i-\bar{q})^2}{n-1}} \tag{14}$$

$$\bar{q} = \sqrt{\frac{\sum_{i=1}^{n}(q_i)^2}{n}} \tag{15}$$

In equations (13), (14), (15): S - standard deviation; $\bar{q}$ - the average number of samples in the unit area of the mesh granular organic fertilizer; n - total number of cell grids in the entire sampling area; q_i-the number of samples in the *i-th* unit lattice region granular organic fertilizer;

To better reflect the distribution of granular organic fertilizer in the entire sampling area, the discrete coefficients of the 1th row, and the 15th row are selected as a reflection of the edge area of the organic fertilizer distribution, discrete coefficients of 5th row, 8th row, 11th row are used as a parameter to reflect the uniformity of granular organic fertilizer distribution in the middle region.

Experiment and Analysis

Firstly, the fertilizer guiding mechanism was introduced into the EDEM simulation software and the relevant parameters were set. In order to obtain the effect of the granular organic fertilizer passing through the fertilizer guiding mechanism into the ditch, an open groove of 1000mm in length, 300mm in width and 400mm in depth was set to simulate the ditching of the ditching and fertilizing machine. The open groove was located directly below the export of the fertilizer guiding mechanism, wherein the axis was in the same vertical plane as the central axis of the fertilizer guiding mechanism, and the bottom of the opening groove was 200mm away from the export of the fertilizer guiding mechanism. Secondly, the fertilizer guiding mechanism was set as a random granules' generator, so that granular organic fertilizer was randomly generated at the opening port in the simulation process. Among them, the granular organic fertilizer was randomly generated with an average equivalent diameter of 2.92mm as the mean value, a minimum equivalent diameter of 2.42mm, and a maximum equivalent diameter of 3.79mm. Finally, the motion characteristics of the assembly was set up. According to the principle of relative motion, the motion of the assembly was converted into the relative motion of the geometry, that is, the open groove moved in a reverse direction with respect to the fertilizer guiding mechanism at a speed of 0.25m/s *(Jin Yuan et al, 2014)*.

In the simulation experiment, in order to ensure the accuracy of the test data under different structural parameters, the total simulation time was set to 2s, the fixed time step was set to 20%, and the target storage interval was set to 0.04s. The material of the mechanism was set to steel, and the relevant material parameters in the test were shown in Table 3. The dynamic friction coefficient and the static friction factor between the material granules and the different materials were determined by the shear box method and the bevel method respectively. The dynamic and static friction factor measurement test of the material granules and each material was repeated three times, and the test results were averaged. The free fall was utilized. The method was used to determine the collision recovery coefficient between material granules and different materials. The collision recovery coefficient determination test of material granules and the same material was repeated three times, and the test results were averaged. The contact mechanical parameters between different materials are shown in Table 4.

Parameter of material   **Table 3**

Parameter	Granular organic fertilizer	Fertilizer guiding mechanism	Land
Poisson ratio	0.25	0.45	0.50
Shear modulus [Pa]	1×10^7	1×10^6	1×10^8
Density [kg·m^{-3}]	1300	3500	1200

Parameter of contact mechanics between materials   **Table 4**

Parameter	Granular organic fertilizer—Granular organic fertilizer	Granular organic fertilizer—Fertilizer guiding mechanism	Granular organic fertilizer—Land
Recovery coefficient	0.10	0.45	0.02
Static friction factor	0.30	0.30	1.25
Dynamic friction factor	0.25	0.20	1.25

Test and Analysis of Different Shapes of Fertilizer Plug-in Plate

In the fertilizer guiding mechanism, the fertilizer plug-in plate was one of the important factors affecting the uniformity of fertilization. The fertilizer plug-in plate of the existing linear fertilizer guiding mechanism was a linear type, and on this basis, a concave and a convex fertilizer guiding mechanism are proposed. Among them, the fertilizer plug-in plate of the concave fertilizer guiding mechanism was a concave curve type, and the fertilizer plug-in plate of the convex fertilizer guiding mechanism was a convex curved type, and the three fertilizer plug-in plates basically covered most guiding fertilizer insertion boards, which covered the main possible types of fertilizer plug-in plates, namely the concave, linear, and convex fertilizer guiding mechanisms, shown in Fig. 8.
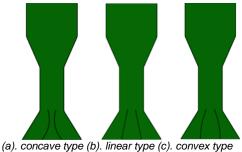

(a). concave type (b). linear type (c). convex type

Fig. 8 - Diagrammatic sketch of three fertilizer guiding mechanisms

The shape of the fertilizer plug-in plate in the fertilizer guiding mechanism was taken as a single factor variable, and other parameters were unchanged. The simulation tests were carried out on the concave, linear and convex fertilizer guiding mechanisms respectively. Among them, the radius of curvature of the fertilizer plug-in plate of the concave and the linear fertilizer guiding mechanism was set to 350mm.
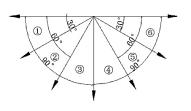
At 1s, the velocity directions of 330 granular organic fertilizers at the fertilizer outlets of the concave, linear and convex types were measured, as shown in Table 5. Among them, the range of the velocity direction is -1~1 in the EDEM simulation software. Based on the horizontal speed, the entire speed plane was equally divided into six parts at intervals of 30°, as shown in Fig. 9.

The speed direction in Table 5 through $\angle\alpha = \frac{v_{fi}}{2} \times 180°$ was converted to the speed plane of Fig. 9, and the amount of granular organic fertilizer in each part was counted.

"$\angle\alpha$"is the angle between the velocity direction of the granular organic fertilizer and the horizontal velocity direction; "v_{fi}"-the speed direction of the i-th granular organic fertilizer.

The velocity distribution map of different parts of granular organic fertilizer was drawn, as shown in Fig. 10.

Velocity direction of granular organic fertilizer   **Table 5**

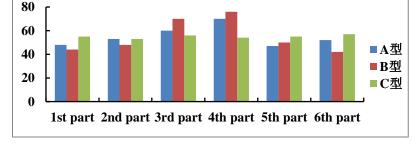| Item	Velocity direction of granular organic fertilizer in concave fertilizer guiding mechanism	Velocity direction of granular organic fertilizer in linear fertilizer guiding mechanism	Velocity direction of granular organic fertilizer in convex fertilizer guiding mechanism
Minimum value	-0.98	-0.98	-0.98
Maximum value	0.99	0.99	0.99
Average value	0.18	0.34	0.13
Variance	0.35	0.40	0.30

Fig. 9 - Partition of velocity direction   **Fig. 10 Distribution of velocity direction in different parts**

It can be seen from Fig.10 that in the concave and linear fertilizer guiding mechanism, the granule direction of the granular organic fertilizer is distributed in the third and fourth parts, and the number of granules is higher than the first, second, fifth and sixth parts.

In the convex fertilizer guiding mechanism, the granule direction distribution of the granular organic fertilizer is almost equal in the number of granules in each part. The granular organic fertilizer in the first and sixth parts of the velocity direction is concentrated on both sides of the bottom of the ditch when falling into the bottom of the ditch; the granular organic fertilizer in the third and fourth parts of the velocity direction is concentrated in the bottom of the ditch when falling into the middle part of the bottom of the ditch; the granular organic fertilizer in the second and fifth parts of the velocity direction is concentrated in the middle of the ditch when falling into the bottom of the ditch. In the concave and linear fertilizer guiding mechanism, when the granular organic fertilizer falls into the bottom of the ditch, it is concentrated in the middle part of the ditch, and the distribution on both sides is less, resulting in uneven distribution of granular organic fertilizer; in the convex fertilizer guiding mechanism, the velocity direction of the granular organic fertilizer is distributed evenly in all parts, and the distribution after falling into the bottom of the groove is relatively uniform.

In order to further evaluate the uniformity of fertilization, the discrete coefficients of the edge region and the middle region in the sampling area were calculated and counted. The results of the discrete coefficients of the edge regions of different fertilizer guiding mechanisms are shown in Table 6. The discrete coefficients of the middle regions of different fertilizer guiding mechanism are shown in Table 7.

Table 6

CV of different fertilizer guiding mechanisms in edge region

Edge region	CV of concave fertilizer guiding mechanism	CV of linear fertilizer guiding mechanism	CV of convex fertilizer guiding mechanism
1st row	0.57	0.43	0.36
15th row	0.50	0.54	0.43

Table 7

CV of different fertilizer guiding mechanisms in middle region

Middle region	CV of concave fertilizer guiding mechanism	CV of linear fertilizer guiding mechanism	CV of convex fertilizer guiding mechanism
5th row	0.43	0.50	0.29
8th row	0.42	0.52	0.32
11th row	0.42	0.49	0.28

From the discrete coefficients of each region in the sampling area, it can be seen that in the three concave, linear and convex fertilizer guiding mechanisms, the discrete coefficients of the edge region and the middle region of the convex fertilizer guiding mechanism are lower than the concave and linear guides. The discrete coefficient of each part of the fertilizer guiding mechanism has the highest uniformity of fertilization.

The shape of the fertilizer plug-in plate changes the speed direction of the granular organic fertilizer, thereby affecting the uniformity of fertilization. The convex fertilizer plug-in plate is superior to the linear and concave fertilizer plug-in plate, and the convex fertilizer guiding mechanism is optimal.

Test and Analysis of the Fertilizer Plug-in Plate with Different Curvature Radius

In order to further determine the influence of the fertilizer plug-in plate with different curvature radius on the fertilization uniformity in the convex fertilizer guiding mechanism, the radius of curvature of the fertilizer plug-in plate was taken as a single factor variable, with a radius of curvature of 150mm~800mm at intervals of 50mm. The simulation experiment was carried out on the fertilizer plug-in plate, and the simulation results are shown in Fig. 11, 12.

The discrete coefficients of the edge region and the middle region under different curvature radius were analyzed, as shown in Table 8.
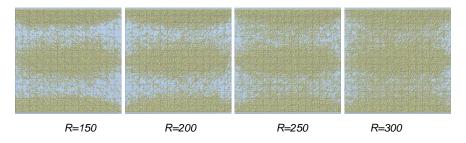

R=150   *R=200*   *R=250*   *R=300*

Fig. 11 Simulation result under different curvature radius

R=350   *R=400*   *R=450*   *R=500*

R=550   *R=600*   *R=650*   *R=700*

R=750   *R=800*   *R=850*   *R=900*

Fig. 12 - Simulation result under different curvature radius

Table 8

CV under different curvature radius

Curvature radius	Edge region		Middle region		
	1st row	15th row	5th row	8th row	11th row
150	0.99	1.02	0.81	0.82	0.86
200	0.73	0.82	0.67	0.66	0.67
250	0.64	0.54	0.52	0.54	0.54
300	0.53	0.50	0.44	0.39	0.44
350	0.36	0.44	0.29	0.32	0.28
400	0.30	0.32	0.25	0.24	0.30
450	0.21	0.38	0.25	0.21	0.23
500	0.23	0.37	0.19	0.16	0.19
550	0.18	0.31	0.15	0.21	0.16
600	0.19	0.29	0.20	0.18	0.15
650	0.21	0.39	0.16	0.15	0.19
700	0.24	0.36	0.21	0.19	0.17
750	0.28	0.28	0.17	0.20	0.21
800	0.25	0.37	0.14	0.18	0.17

It can be seen from Table 8 that when the radius of curvature is in the range of 150mm~550mm, the discrete coefficient of the edge region and the middle region is gradually decreased; when the radius of curvature is in the range of 550mm~800mm, the discrete coefficient of the edge region and the middle region does not change much; the radius of curvature of the fertilizer plug-in plate affects the uniformity of fertilization within a certain range.

To further describe the relationship between the radius of curvature and the uniformity of fertilization, a cubic polynomial was used to fit the discrete coefficient curves of the edge region and the middle region.

First, at different radius of curvature, the average of the discrete coefficients of the first row and the 15th row is taken as the feature point of the discrete coefficient of the edge region; secondly, at the different radius of curvature, the discrete coefficient of the fifth row, the eighth row, the 11th row is averaged and used as the feature point of the middle region discrete coefficient. Finally, the cubic polynomial fitting is performed on the feature points of the edge region and the middle region to obtain the discrete coefficient fitting curve between the edge region and the middle region.

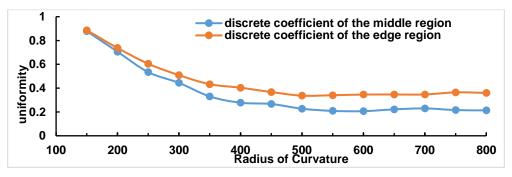The results of the discrete coefficient fitting are shown in Fig. 13.

Fig. 13 - Fitting curve of CV

It can be seen that the edge region fitting discrete coefficient obtains a minimum value when the radius of curvature is 566mm, and the middle region fitting discrete coefficient obtains a minimum value when the radius of curvature is 596mm. In order to ensure that the discrete coefficients of edge and middle regions are minimized, and combined with processing technology and cost, the optimal curvature radius is finally determined to be 600 mm.

In the convex fertilizer guiding mechanism, the radius of curvature of the fertilizer plug-in plate affects the uniformity of fertilization. Under the processing conditions, when the radius of curvature of the fertilizer plug-in plate is 600mm, the cost is low and the uniformity of fertilization is high.

Field Trials

In mid-June 2017, a field trial was conducted in the experimental farm of Henghe in Shandong Province, as shown in Fig. 14. The farm was a large-scale standardized planting of orchard, with a row spacing of 2.5m and a plant spacing of 1m. The Plant was 3 years old and grew well. The test site was loam, the soil had an absolute moisture content of 23.3%, the soil firmness was 76.0kPa, and the terrain was flat, which provided favourable conditions for the smooth progress of the test. The test prototype was a two-row ditching and fertilizing machine for the orchard. The fertilizer guiding mechanism was a linear fertilizer guiding mechanism before optimization and an external convex fertilizer guiding mechanism with a radius of curvature of 600mm. In order to ensure the accuracy of the experimental data, three regions were randomly selected, and repeated verification tests of three discrete coefficient measurements were performed for each region, and the discrete coefficient curves before and after optimization were plotted, as shown in Fig. 15.

(a). Field operation　　*(b). Fertilization effect in sampling area before and after optimization*
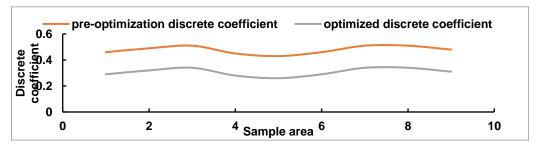**Fig. 14 - Field Test**

Fig. 15 - CV curve before and after optimization in different regions

The experimental results show that the optimized discrete coefficient curve is below the pre-optimization discrete coefficient curve. The optimized discrete coefficient is significantly smaller than the pre-optimization discrete coefficient. The average value of the discrete coefficient of the sampled area before optimization is 0.51. The average value of the discrete coefficient of the sampled area after optimization is 0.26. Fertilization uniformity increased by 49.02%.

After optimizing the parameters of the fertilizer guiding mechanism, under the conditions of the same ditch depth and speed, the discrete coefficient of the sampling area is reduced, the uniformity of fertilization is improved, and the technical requirements for the ditching and fertilization of the orchard are satisfied.

CONCLUSIONS

(1) Based on the existing linear fertilizer guiding mechanism, two other fertilizer guiding mechanisms, a concave fertilizer guiding mechanism and a convex fertilizer guiding mechanism are proposed.

(2) By using the shape of the fertilizer plug-in plate as a single factor variable, the three kinds of fertilizer guiding mechanisms of concave, linear and convex type are simulated respectively to determine that the convex fertilizer plug-in plate of the convex fertilizer guiding mechanism has the best shape and its uniformity of fertilization is the highest. Among them, the shape of the fertilizer plug-in plate affects the uniformity of fertilization by changing the velocity direction of the granular organic fertilizer.

(3) By using the radius of curvature of the fertilizer plug-in plate as a single factor variable, the simulation experiment is carried out on the convex fertilizer guiding mechanism with the radius of curvature of 150mm~800mm, and the polynomial is used to fit the discrete coefficient of the edge region and the middle region to determine the curve. The convex fertilizer guiding mechanism has an optimum radius of curvature of 600 mm. According to the field test, the discrete coefficient after optimization was reduced from 0.51 to 0.26, and the uniformity of fertilization was increased by 49.02%.

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REFERENCES

[1]   Aphale A., Bolander N., Park J., Shaw L., Svec J., Wassgren C., (2003), Granular fertilizer particle dynamics on and off a spinner spreader. *Biosystems Engineering*, pp.319-329;

[2]   Chen X.F., Luo X.W., Wang Z.M., Zhang M.H., Hu L., Yang W.W., Zeng S., Zang Y., Wei H.D., Zheng. L., (2015), Design and experiment of fertilizer distribution apparatus with double-level screws. *Transactions of the Chinese Society of Agricultural Engineering* , issue 31, pp.10-16;

[3]   Cunningham F.M., (1963), Performance characteristics of bulk spreaders for granular fertilizer. *Transactions of the ASAE*, issue 6, pp.108-114;

[4]   Gao J.S., Xu M.G., Wang B.R., Qin D.Z., Wen S.L., Shen H.P., (2005), Combined fertilization of chemical and organic fertilizers in a long-term position experiment, *Chinese Agricultural Science Bulletin*, vol.21, issue 9, pp.211-214;

[5]   Han D.Y., Lv Z.Q., Cui F.F., Shen X., (2010), Design of the Fertilizing Machine for Fruit Trees, *Journal of Agricultural Mechanization Research,* vol.32, issue 12, pp.65-68;

[6]   Inns F.M., Reece A. R., (1962), The theory of the centrifugal distributor II: motion on the disc, off-centre feed. *Journal of Agricultural Engineering Research* , issue 7, pp.345-353;

[7]   Liedekerke P. Van., Tijskens E., Dintwa E., Rioual F., Vangeyte J., Ramon H., (2009), *Powder Technology*, issue 190, pp.348-360;

[8]   Li M., Zhang T., Dong X.H., Wang C., Niu Z.J., Ge C., Wei L.J., (2016), Parameter optimization on scraper fertilizer feed unit of 3ZSP-2 type sugarcane intertillage fertilizer applicator-cum-hiller. *Transactions of the Chinese Society of Agricultural Engineering* , issue 32, pp.36-42;

[9]   Liu B., Xiao H.R., Song Z.Y., Mei S., (2017), Present State and Trends of Fertilizing Machine in Orchard. *Journal of Agricultural Mechanization Research* , issue 39, pp.263-268;

[10]   Lv J.Q., Wang Z.M., Sun X.S., Li Z.H., Guo Z.P., (2015), Design and Experimental Study of Feed Screw Potato Planter Propulsion. *Journal of Agricultural Mechanization Research* , issue 6, 194-196;

[11]   Ma C., Meng H.W., Kan Z., Qi J.T., (2017), Design of Jujube Harvest Test Device Based on Self-excited Vibration and Force Compensation, *Journal of Agricultural Mechanization Research,* vol.39, issue10 , pp.12-17;

[12]   Ma J., Yan H.J., Wang, C.Y., (2016), Effect of end gun on/off on variable rate fertigation uniformity and its improvement for centre pivot irrigation system, *Journal of Hydraulic Engineering*, issue 12, pp.1577-1584;

[13]   Patterson D.E., Reece A.R. The theory of the centrifugal distributor. I: Motion on the disc, near-centre feed., (1962), *Journal of Agricultural Engineering Research*, issue 7, pp.232-240;

[14]   Pitt R.E., Farmer G.S., Walker L.P., (1982), Approximating equations for rotary distributor spread patterns. *Transactions of the ASAE* , issue 25, pp.1544-1552;

[15]   Przywara Artur., (2015), The Impact of Structural and Operational Parameters of the Centrifugal Disc spreader on the Spatial Distribution of Fertilizer. *Agriculture and Agricultural Science Procedia*, issue 7, pp.215~222;

[16]   Qi W.Z., Wang J.X., Liu. S.X., Wang Y.L., Wang Z., Zhao G.X., (2019), Design and Experiment of Control System for Rice and Wheat Variable Rate Fertilizer Applicator. *Journal of Agricultural Mechanization Research* , issue 41, pp.72-79;

[17]   Shi Y.Y., Chen M., Wang X.C., Morice, O., Li C.G., Ding, W M., (2018), Design and Experiment of Variable-rate Fertilizer Spreader with Centrifugal Distribution Cover for Rice Paddy Surface Fertilization, Transactions of the Chinese Society for Agricultural Machinery, vol.49, issue 3, pp.86-93+113;

[18]   Villette S., Piron E., Martin R., Courreau D.,Miclet D., Gée C., (2010), Impact recording system to characterize centrifugal spreading. *Book of Abstracts*;

[19]   Zhang T., Liu F., Liu Y.Q., Zhao M.Q., Zhang S., Li N., Li L.F., Lv B., (2015), Discrete Element Simulation of Outer Groove Wheel Type Fertilizer Discharging Device Capacity Analysis. *Journal of Agricultural Mechanization Research* , issue 9, pp.198-201;

[20]   Zhao L.Y., (2002), Study on the Text System of Virtual Instrument for Precision Seed-Metering Device, MS Thesis, Nanjing: Nanjing Agricultural University;

[21]   Zheng X.C., Lu H.J., Che J.X., Zhai B.N., Zhao Z.Y., Wang, Y.L., (2011), Investigation of present yield and fertilization on Fuji apple in Baishui County, *Journal of Northwest A&F University*, vol.39, issue 9, pp.145-151;

[22]   Zhou Z., Fu Z.T., Wang X., Zheng L.J., (2009), Experiment of fertigation uniformity of drip fertigation machine. *Transactions of the Chinese Society of Agricultural Engineering* , issue 25, pp.7-13;

[23]   Wu N., Wu D.S., Li H., Liang H., (2016), Calibration of Manure Spreaders. *Journal of Agricultural Mechanization Research*, vol.38, issue 9 , pp.255-259;

[24]   Yuan J., Liu Q.H., Liu X.M., Zhang T., Zhang X.H., (2014), Simulation of Multi-fertilizers Blending Process and Optimization of Blending Cavity Structure in Nutrient Proportion of Variable Rate Fertilization. *Transactions of the Chinese Society for Agricultural Machinery* , issue 45, pp.125-132;

[25]   Yuan J., Liu Q.H., Liu X.M., Zhang T., Zhang X.H., (2014), Granular Multi-flows Fertilization Process Simulation and Tube Structure Optimization in Nutrient Proportion of Variable Rate Fertilization. *Transactions of the Chinese Society for Agricultural Machinery*, issue 11, pp.81-87;

[26]   Yang X.L., Wang J.W., Wang J.F., Zhou W., (2015), Parameters Optimization Design and Analysis of Vaned Fertilizer Distributing Device. *Journal of Agricultural Mechanization Research*, issue 7, pp.160-163;

[27]   Yuan W.S., Li K., Jin C.Q., Hu M.J., Zhang W.Y., (2018), Design and Experiment of Hill Placement Fertilizer Applicator. *Journal of Agricultural Mechanization Research*, issue 40, pp.145-149.