Simulation analysis of the fertilizer ejecting device of corn fertilizer applicator based on EDEM

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\textbf{Abstract.} In order to improve the fertilization efficiency of corn fertilizer applicator in the Huang-Huai-Hai area, according to the requirements of the wide-row crop fertilizer requirements, a centralized type fertilizer ejecting device was designed. Straight outer groove-wheel was regarded as research objects in this paper. The simulation model of fertilizer ejecting device was established and the simulation analysis of fertilizer ejecting was carried out by using the discrete element simulation software (EDEM). In the simulation environment, the requirement of fertilizer ejecting amount was 300kg·hm\textsuperscript{-2}, the forward speed of fertilizer ejecting device was set to 5.4km·h\textsuperscript{-1}, and the working height of fertilizer axis was 250mm. The effect of different working lengths of fertilizer ejecting wheels on the fertilizer performance was analyzed. The simulation results showed that when the working length of fertilizer ejecting wheel was 28mm, the uniformity variation coefficient of fertilizer ejecting was 14.62\%, and the accuracy rate of fertilizer ejecting was 95.95\%, which indicated that performance of fertilizer ejecting was better. This research results can provide references for the subsequent development of corn fertilizer applicator.

1. \textbf{Introduction}
Top dressing is an important part in the process of crop production management. The late top dressing management in corn can effectively reduce the application amount of base fertilizer, improve the utilization rate of fertilizer, and decrease environmental pollution. Mechanized top dressing can effectively improve the efficiency of fertilization operation and reduce labor intensity. In addition, it also improves the comprehensive economic benefits [1-3].

At present, most of the foreign corn fertilizer applicators adopt centralized fertilization device for top dressing operation. It is mainly based on the models of American companies such as John Deere, AGCO, and Salford. Their fertilizer applicators have many advantages of high integration degree, good controllability of operation, working amplitude, and high fertilization efficiency. However, the machines have some disadvantages of expensive price, complicated structure, inconvenient of replacing accessories, and large difference in agronomy at home and abroad, which limits the popularization and application of foreign machinery in China. In recent years, domestic scholars have also conducted related researches on fertilizer applicator. A targeted fertilizer applicator was designed
by Hu Hong and the others to study the fertilizer of hole-pricking for corn [4]. The targeted fertilizer was completed by the outer groove wheel with interval fertilizer ejecting and the slide rail-link with interval vertical movement, which improves the utilization rate of fertilizer. However, the efficiency of fertilizer applicator was lower. An electric corn intertillage fertilizer applicator was designed by the team of Zheng Yuanyuan [5]. Fertilizer is ejected by using a common outer groove wheel fertilizer apparatus, and the furrow fertilization operation is carried out by using a single furrow opener, which can smoothly realize the mechanized top dressing operation between corn rows. However, the efficiency of top dressing needs to be improved. With the development of computer technology, discrete element method (DEM) and simulation software (EDEM) are widely used in the field of agricultural engineering. It provides new ideas for the research of fertilizer ejecting device. Van Liedekerke and the others had studied the movement of fertilizer particles during the fertilizer ejecting by using EDEM software. The movement of individual fertilizer particle was analyzed in simulation, and the experiments of fertilizer ejecting were carried out for the comparison [6]. The effects of the working length of the outer groove wheel and the opening angle of the fertilizer tongue on the amount of fertilizer had been studied with the method of discrete element and regression test by Wang Botao and the others [7]. The fertilizer simulation on the fertilizer ejecting device with outer groove wheel had been conducted by the team of Yang Zhou using EDEM [8]. The influence of structural parameters such as the radius of groove and helix rise angle on fertilizer ejecting was studied. Based on the simulation technology of discrete element, the influence regularity of 4 key structural parameters such as groove wheel radius, groove numbers, effective working length and cross-sectional shape of the groove on fertilizer performance was analyzed by Zhu Qingzhen and the others [9]. And the interaction among the parameters had been determined finally.

In general, the research of corn fertilizer applicator is still in the experimental stage in China. Most of the research content is on the study of the fertilizer performance of traditional fertilizer ejecting device. There are few reports on the structural design and optimization of new fertilizer ejecting device. Moreover, the efficiency of fertilization needs to be improved. In order to improve the efficiency of fertilization, a centralized type of fertilizer ejecting device was designed in this paper. On the basic of EDEM software, the fertilizer ejecting performance was analyzed, and the structural parameters of the fertilizer ejecting wheel were optimized, which ensured the rationality of the design of fertilizer ejecting device.

**Figure 1.** Schematic diagram of centralized distributing fertilizer applicator and fertilizer ejecting device for corn.

1- Fertilizer box 2- Fan 3- Control system 4- Centralized fertilizer ejecting device 5- Fertilizer conveying device 6- Fertilization fixed frame 7- Rack 8- Walking wheel 9- Ground 10- Fertilization shovel 11- Fertilization pipe 12- Fertilizer ejecting motor 13- Barrier plate 14- Fertilizer ejecting wheel 15- Spacer plate 16- Lower fertilizer ejecting groove 17- Fertilizer ejecting shell 18- Upper fertilizer ejecting groove
2. Fertilizer ejecting device and working principle

2.1. Composition of structure
The structure of the corn fertilizer applicator was shown in Figure 1(a), which mainly included the fertilizer box, fan, fertilization control system, airflow allotter, centralized fertilizer ejecting device, feeder, fertilization fixed frame, rack, fertilization shovel, walking wheel and fertilizer pipe. In order to achieve multi-row centralized fertilizer ejecting, a new type of centralized fertilizer ejecting device was designed in this paper. The structure of the centralized fertilizer ejecting device was shown in Figure 1(b), which mainly consisted of the fertilizer ejecting motor, barrier plate, fertilizer ejecting wheel, Spacer plate, lower fertilizer ejecting groove, fertilizer ejecting shell and upper fertilizer ejecting groove. The fertilizer ejecting device adopted the structure form of 6-row fertilizer ejecting wheels for centralized fertilizer ejecting, and the structural integration degree was relatively high. In addition, a fertilizer ejecting motor could be used to control multi-row amount of fertilizer ejecting consistently. The fertilization amount of each fertilization shovel came from the amount of fertilizer ejected by the corresponding fertilizer ejecting wheel, which can ensure a better consistency of fertilizer ejecting between rows.

2.2. Fertilizer ejecting principle
Fertilizer ejecting wheel is the main working part of the fertilizer ejecting mechanism. At present, there are many types of structure in commonly used fertilizer ejecting wheels. Because the outer groove wheel of straight-tooth has some advantages of simple structure, high controllable amount of fertilizer, and stable working performance, it was adopted for the design of fertilizer mechanism in this paper. The fertilizer ejecting groove redesigned was composed of the upper and lower arc plates, which replaced the fertilizer tongue in the traditional fertilizer ejecting device. The fertilizer ejecting wheel could be wrapped exactly, which could reduce amount of fertilizer within the driven layer during fertilizer ejecting. Moreover, the design cornerite of upper and lower arc plates at least exceeded the pitch angle between adjacent grooves, which could avoid the fertilizer leaking from the same groove when the groove wheel stops in a critical state. The schematic diagram of the fertilizer ejecting process was shown in Figure 2. According to the working principle of the outer groove wheel [10-11], the amount of fertilizer ejecting per revolution of single fertilizer wheel was shown in Formula (1).

\[
\begin{align*}
q &= \pi dl\gamma\left(\frac{\varphi f_s}{\omega} + \lambda\right) \\
\omega &= \frac{\pi d}{z}
\end{align*}
\]

where, \( q \) is the fertilizer amount per revolution of single groove-wheel (g·r⁻¹), \( d \) is the outer diameter of groove-wheel (mm), \( l \) is the working length of single groove-wheel (mm), and \( \gamma \) is bulk density of fertilizer (g·mm⁻³), \( \varphi \) is the filling coefficient of fertilizer in the groove, \( f_s \) is the cross-sectional area of groove of single groove-wheel (mm²), \( \omega \) is groove pitch (mm), \( z \) is the groove number of groove-wheel, \( \lambda \) is the characteristic coefficient of driven layer (mm).

![Figure 2. Working principle diagram of fertilizer ejecting device.](image)

1- Fertilizer ejecting shell 2- Blocking plate of fertilizer 3- Upper arc plate of groove 4- Fertilizer ejecting wheel 5- Fertilizer ejecting shaft 6- Brush 7- Lower arc plate of groove
According to the Formula (1), the main parameters affecting the amount of fertilizer ejecting were the cross-sectional area of groove, the working length of groove-wheel and filling coefficient of groove. When the amount of fertilizer ejecting was constant, the requirements of the working length and rotation speed of the groove-wheel would become smaller if the cross-sectional area of groove was larger. And the uniformity of the amount of the fertilizer ejecting was relatively poor. If the cross-sectional area of groove was small, the requirements of the rotation speed and working length of the fertilizer ejecting wheel would become larger. And then the filling coefficient of fertilizer was decreased so that the accuracy of fertilizer ejecting was relatively reduced. According to the size of fertilizer particle and the agronomic requirements of top dressing for corn, the commonly used straight groove-wheel on the market (outer diameter of fertilizer wheel being 68mm, number of groove per week being 6, groove depth being 21.5mm, thickness between outer grooves being 4mm, groove radius being 8.5mm) was selected. The process of fertilizer ejecting was simulated in the EDEM software. The uniformity and the accuracy of fertilizer were regarded as the performance evaluation index to optimize the effective working length of fertilizer wheel.

3. Discrete element simulation analysis

3.1. Parameter model of the fertilizer particle

Urea fertilizer is mainly used in corn topdressing in Huang-Huai-Hai region, so urea particles are regarded as experimental materials for simulation analysis of fertilizer ejecting in this paper. 100 urea granules were randomly picked for dimension measurements. Referring to the three-dimensional modelling method of particles [12-13], length, width, and thickness of urea granules were measured by using the measurement tool. After the particle size measurement completed, the average value of the particle length, width and thickness were obtained, which were 2.46mm, 2.31mm and 2.37mm, respectively. And the equivalent diameter ($D$) and spherical ratio ($\eta$) were calculated 2.38 mm and 96.39% respectively according to the following Equation (2).

\[
\begin{align*}
D &= \sqrt[3]{LWT} \\
\eta &= \frac{D}{L}
\end{align*}
\]

where, $D$ is the equivalent diameter of the fertilizer particles (mm), $L$, $W$, and $T$ are the length, width, and thickness of the fertilizer particles (mm), $\eta$ is the spherical rate of the fertilizer particles (%).

3.2. Contact model and parameters of the discrete element

In the simulation analysis of particle motion by EDEM software, the default model of Hertz-Mindlin (no slip) was used for particles and particles, particles and shell (including fertilizer box, fertilizer wheel, fertilizer tank and fertilizer pipe) and particles and ground, because there was no binding effect between fertilizer particles. And the shell material belonged to the PLA material in the simulation model. Combined with the test measurement and literature review, the related material properties and contact mechanics parameters of the fertilizer, shell and ground needed in EDEM were determined [9, 14-15], as shown in Table 1. In addition, the value and direction of gravity acceleration must be set in the software according to the actual situation.

**Table 1. Characteristic parameters of discrete element model.**

| Parameters        | Poison ratio | Shear modulus (Pa) | Density (kg·m⁻³) | Restitution coefficient (Interaction with particle) | Static friction coefficient (Interaction with particle) | Rolling friction coefficient (Interaction with particle) |
|-------------------|--------------|--------------------|------------------|-----------------------------------------------------|--------------------------------------------------------|--------------------------------------------------------|
| Fertilizer particle | 0.25         | 3.2E+07            | 1335             | 0.32                                                | 0.43                                                   | 0.12                                                   |
| Fertilization device | 0.41         | 1.3E+09            | 1260             | 0.41                                                | 0.32                                                   | 0.18                                                   |
| Soil              | 0.3          | 1.0E+06            | 1800             | 0.02                                                | 1.25                                                   | 1.24                                                   |
3.3. **Discrete element model and simulation analysis**

The centralized fertilizer ejecting device designed in this paper was composed of multi-row side by side, the fertilizer ejecting wheel had the same specifications, and the input power came from the same motor, so the fertilizer ejecting state of each row could keep consistent. In order to reduce the calculation amount of simulation, the centralized fertilizer ejecting device was simplified as a single-row fertilizer device the simulation environment. First, the 3D model of the single-row fertilizer ejecting device was exported to IGS format by 1:1 scale. Then, the exported model was imported EDEM software (EDEM2.7 in this article). And related settings were carried out according to the parameters in Table 1. In order to truly reflect the effect of the fertilizer ejecting device on the ground, a soil layer with a length of 2500mm and a width of 200mm was simulated in the simulation environment in this study, which was used to collect the ejected fertilizer particles and record the fertilizer position. The distance from the top surface of the soil to the axis of the fertilizer ejecting wheel was 250mm. Moreover, the axis of the fertilizer ejecting wheel was parallel to the soil surface. The simulation model diagram was shown in Figure 3.

According to the agronomic requirements of corn fertilizer in Huang-Huai-Hai area, the fertilizer ejecting amount of the fertilizer applicator was 300kg hm⁻² and the forward speed of top dressing was 5.4km h⁻¹. And the corresponding parameter settings were set in the simulation environment. Three simulation models with different working length of groove-wheel were established (l₁ = 14mm, l₂ = 21mm, l₃ = 28mm). According to the Formula (1), the theoretical speeds of the three groove-wheels were 60r·min⁻¹, 40r·min⁻¹ and 30r·min⁻¹ (when φ was 0.95 and λ was 0.3). A particle factory was set above the shell to provide fertilizer particles required during fertilizer ejecting process. The particle factory could produce 20,000 fertilizer particles per second, for a total number of 50,000 particles. The diameter of the fertilizer particles generated followed the normal distribution. After a certain amount of particles was generated, the fertilizer ejecting wheel and the fertilizer device started to move, and the total simulation time was 3.5s. The simulation analysis of the fertilizer apparatus was shown in Figure 3.

![Figure 3. Simulation of working process for fertilizer apparatus.](image)

1- Fertilizer ejecting shell 2- Fertilizer ejecting wheel 3- Fertilizer particles 4- Ground

4. **Analysis of simulation results**

4.1. **Evaluation method of fertilizer performance**

In order to properly select the working length of the fertilizer wheel, it is necessary to set up an appropriate evaluation method in the EDEM environment. According to the NY/T 1003-2006 “technical specification for quality evaluation of fertilizer applicator”, the JB/T 7864-2013 “intertillage-fertilizer applicator” and the GB/T 20346.2-2006 “test methods for fertilizer applicator” Part 2 with interrow fertilizer applicator and other related test methods, the uniformity and the accuracy of fertilizer ejecting were selected as the performance evaluation index of the fertilizer ejecting device in this paper. A sampling area (length of 1500mm) was selected in the middle of the simulation ground. And, the sampling area was divided into the sampling grid (Grid Bin Group) with the analyst function of EDEM software. According to the range of corn plant spacing (25mm-30mm), 5 sampling units (each grid unit size 300mm×200mm×100mm) were set in the length direction of the sampling area, and numbered 1 to 5 from left to right (as shown in Figure 4). According to the quality
of the fertilizer in the sampling grid, the evaluation of fertilizer performance was carried out. The greater the uniformity of fertilizer and the higher the accuracy of fertilizer got, the better the fertilizer performance became.

![Figure 4](image-url). Sampling method of simulation results.

**4.2. Analysis of fertilizer performance**

After the simulations of the three fertilizer models were completed, the quality of the fertilizer in the sampling grid was counted separately and marked as \( m_i \) in the \( i \)-th sampling grid (\( i \) was taken the value 1 to 5). Moreover, the uniformity of fertilizer was calculated according to Formula (3). The smaller the coefficient of variation of the fertilizer uniformity (\( S_{cv} \)) was, the better the fertilizer ejecting uniformity became.

\[
\begin{align*}
    m &= \frac{\sum_{i=1}^{n} m_i}{5} \\
    S_a &= \sqrt{\frac{\sum_{i=1}^{n} (m_i - m)^2}{4}} \\
    S_{cv} &= \frac{S_a}{m} \times 100% \tag{3}
\end{align*}
\]

where, \( m \) is the average quality of fertilizer in the sampling grid (g), \( i \) is the sampling grid number, which is 1, 2, ... 5; \( m_i \) is the quality of the fertilizer in the \( i \)-th grid (g), \( S_a \) is the standard deviation of fertilizer quality in all sampling grids (g), \( S_{cv} \) is the coefficient of variation of fertilizer quality between sampling grids (%).

The quality of all fertilizers in the sampling range was counted, and the accuracy of fertilizer was calculated according to the Formula (4). Finally, the simulation data of fertilizer discharge under the three models were recorded separately, and the sorting results were listed in Table 2.

\[
\begin{align*}
    W_a &= \left( 1 - \frac{|q_{1a} - q_{2a}|}{q_{1a}} \right) \\
    q_{1a} &= \frac{1000Q \cdot BS}{15 \times 667 \times 6} \tag{4}
\end{align*}
\]

where, \( W_a \) is the accuracy rate of fertilizer in the simulation test (%), \( Q \) is the fertilization amount required for agronomy (kg·hm\(^{-2}\)), \( q_{1a} \) is the theoretical amount of fertilization within the sampling distance (g), \( q_{2a} \) is the simulated amount of fertilization within the sampling distance (g), \( B \) is the width of the topdressing applicator (3.6m), \( S \) is the sampling distance of simulation (1.5m).

**Table 2. Results and analysis of simulation for the fertilizer device.**

| Rotation speed of groove wheel (r·min\(^{-1}\)) | Theoretical amount of fertilizer (g) | Quality of fertilizer in sampling box (g) | Total quality (g) | Average value (g) | Standard deviation (g) | Coefficient of variation (%) | Accuracy (%) |
|-----------------------------------------------|-------------------------------------|------------------------------------------|-------------------|------------------|------------------------|---------------------------|--------------|
| 60                                            | 26.99                               | 4.46 5.60 5.99 5.10 4.44                 | 25.59             | 5.12            | 0.62                   | 12.11                     | 94.79        |
| 40                                            | 26.99                               | 6.56 6.15 4.50 4.78 6.08                 | 28.07             | 5.61            | 0.82                   | 14.62                     | 95.95        |
| 30                                            | 26.99                               | 8.42 2.21 8.49 5.24 4.61                 | 28.97             | 5.79            | 2.40                   | 41.45                     | 92.66        |
It can be seen from the data in Table 2 that when the fertilizer ejecting amount was 300kg·hm⁻² and the forward speed was 5.4km·h⁻¹, the coefficient of variation of the fertilizer uniformity increased with the decrease of the fertilizer rotation speed, and the accuracy rate of fertilizer ejecting increased first and then decreased with the reduction of fertilizer rotation speed. When the rotation speed of fertilizer was 30r·min⁻¹, the coefficient of the variation of fertilizer uniformity was the largest (41.45%), and the accuracy rate of fertilizer ejecting was the smallest (92.66%). When the rotation speeds of fertilizer ejecting were 60r·min⁻¹ and 40r·min⁻¹ respectively, the uniformity of fertilizer ejecting was better, and the difference in coefficient of variation was smaller. Moreover, the accuracy of fertilizer ejecting was higher, and the difference was smaller between the two rotation speeds. When the speed of fertilizer ejecting was 40r·min⁻¹, the accuracy of fertilizer was the highest (95.95%), and the coefficient of variation of fertilizer uniformity was also smaller (14.62%). So the fertilizer ejecting performance of this simulation model was regarded better. Therefore, when the fertilizer ejecting device of the corn fertilizer applicator was designed in this paper, the preferred working length of the fertilizer ejecting wheel was l₅, and its value was 21 mm.

5. Conclusions
(1) In order to meet the requirement of top dressing in the middle-stage of corn production, a concentrated fertilizer ejecting device was designed in this paper. Combining the working principle of fertilizer ejecting, the relationship between the parameters of the fertilizer wheel structure and the fertilizer ejecting performance was analyzed. Based on EDEM software, a discrete element simulation platform was built, and the effects of different working lengths of groove-wheel on fertilizer performance were studied.

(2) The simulation experiments of three kinds of fertilizer models were carried out. The test results showed that there existed a big difference in fertilizer ejecting performance under different rotation speeds of fertilizer ejecting. Within the test range, the coefficient of variation of the fertilizer uniformity increased with the decrease of the fertilizer rotation speed, and the accuracy rate of fertilizer ejecting increased first and then decreased with the reduction of fertilizer rotation speed. When the rotation speed of fertilizer ejecting was 40r·min⁻¹, the accuracy of fertilizer was the highest (95.95%), and the coefficient of variation of fertilizer uniformity was also smaller (14.62%), which indicated fertilizer performance was the best. And then the working length of the fertilizer ejecting wheel was preferred for the fertilizer device in this condition, of which the value was 21mm.

Acknowledgements
This work was funded by the National Key Research and Development Program of China under the grant No. 2016YFD0200608 and 2016YFD0200604. We acknowledged Beijing Academy of Agriculture and Forestry Sciences that provided the research platform to complete this research.

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