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Design of a Sieve Bucket Spreading Mechanism based on EDEM

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Abstract

Spreading mechanism is the final actuator of fertilizer applicators and can influence fertilizer distribution. Common fertilizer spreader mechanisms include fertilizer discharge tube and spreading disc. Fertilizer discharge tube can easily cause separation and its triangular texture causes particle hysteresis. Although fertilizer spreading disc has simple structure, large width, and high efficiency, its performance is vulnerable to external factors. Fertilizers may unevenly distribute among the blades of fertilizer spreading disc. Both mechanisms cannot assure spreading uniformity. Therefore, a sieve bucket spreading mechanism was designed in this study to ensure such uniformity. Moreover, parameters of the sieve bucket spreading mechanism were discussed. A simulation analysis on the working process of this mechanism was performed using the extended discrete element method. The effects of hole shape, ratio between hole distance and hole size, and advancing speed on spreading uniformity were analyzed using the uniformity measurement index. Results indicate that the structure of the designed sieve bucket spreading mechanism was optimized. In addition, the hole shape on this mechanism and the advancing speed of fertilizer applicator influenced spreading uniformity, but the ratio between hole distance and hole size exerted small impacts. The sieve bucket spreading mechanism obtained a small variable coefficient of the fertilizer. Research conclusions provide a new idea and some references for the optimization of the mechanical structure of solid spreader and improvement of spreading accuracy.

Keywords: Sieve bucket mechanism, Uniformity, Discrete Element Method, Advancing Speed

1. Introduction

Fertilizers exert important effects on the increase in crop yields [1]. The current consumption of chemical fertilizers in rural areas in China has reached a relatively high level. However, no appropriate fertilizer applicator is available due to the relatively old technologies for fertilization. Unreasonable fertilization not only causes energy waste but also brings nutrient imbalance, reduced soil fertility, and environmental pollution, thereby influencing the sustainable development of agriculture [2].

Existing fertilizer applicators include centrifugal, grooved wheel, and helix types. To assure the stability and increase the accuracy of fertilization, many studies on centrifugal- and grooved wheel-type fertilizer applicators have been reported, which are mainly based on control theoretical method, discrete element method (DEM), and orthogonal test. Studies on centrifugal disc fertilizer applicators mainly focus on performance improvement by analyzing key parameters (e.g., number of discs and scrapers, angle of scraper, dip angle, installation mode, and position of fertilizer outlet), kinematic and dynamic properties of fertilizers on disc, or after discharge on the basis of the theoretical design and DEM [3-5, 21, 22, 26]. The main objective of the research on centrifugal cone disc fertilizer applicators is to improve spreading uniformity by using the rotating speed of the cone disc, blade length, dip angle, feeding in position, and feeding in angle [6-8]. Meanwhile, studies on grooved wheel fertilizer applicators mainly focus on the control system and mechanical structure of such applicators. Considerable research concerning the control system emphasizes the improvement of fertilization accuracy by optimizing the parameters of the control system on the basis of control theory. Studies on the mechanical structure of fertilizer applicators concentrate on structures such as fertilizer apparatus, mixer, and discharge tube, and the relationship among the parameters of fertilizer applicators on the basis of DEM and orthogonal test [9-13]. Although these studies increase the fertilization efficiency and variable coefficient (C_V) of fertilization to an extent, none of them assures the final spreading uniformity. Therefore, designing a sieve bucket spreading mechanism, which can assure the final fertilization effect and increase spreading uniformity, is of great significance.

2. State of the art

Foreign scholars have recently investigated the structural parameters of a centrifugal disc spreader and its spreading performance. Yildirim et al. [14] analyzed the effects of the parameters of single- and double-disc spreaders (e.g., installation height, dip angle, and rotating speed of discs) and cone discs (e.g., dip angle and rotating speed) on the distribution width and uniformity of fertilizers. However, they have not provided specific measurement indexes. Pet,cu

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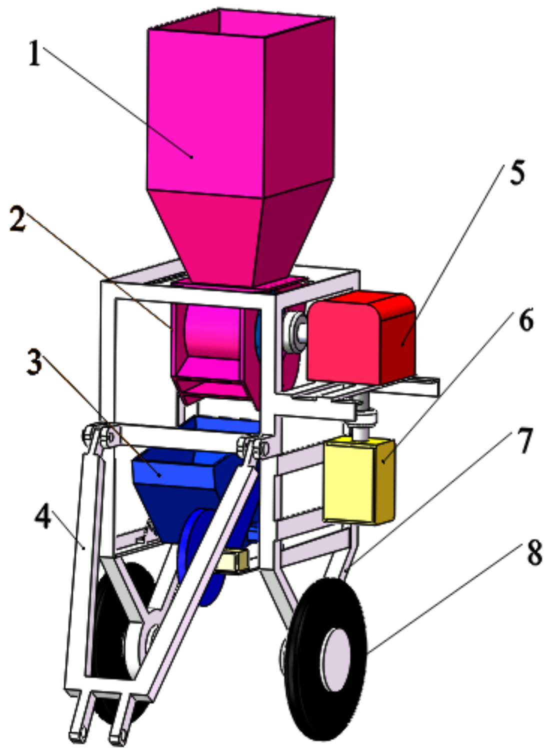
et al. [15] investigated the working process of centrifugal fertilizer management system and enumerated the influencing factors of spreading uniformity. Cool et al. [16, 17] discussed the wind direction, wind speed, and physical properties of fertilizer particles, all of which influence the movement locus of fertilizer by using the 3D trajectory model. Moreover, spreading mode was predicted using a multi-camera stereoscopic visual system, and the result was compared with the given mode, thereby assuring spreading uniformity. Villette et al. [18] constructed a hybrid centrifugal spreading model on the basis of the kinematic equation of fertilizer spreading and statistical information. They also used the model to analyze the influences of outlet velocity, mass flow distribution around the disc, and characteristic parameters of fertilizers on spreading performance. They concluded that the C_V value of the hybrid fertilizer reached 6.1%, in which those of the first and second fertilizer components were 12.5% and 17.1%, respectively. Abbou et al. [19, 20] designed a real-time control device to adjust the horizontal and longitudinal dip angles of the disc to adapt to uneven surfaces and thereby increase spreading uniformity. Moreover, spreading performance under three different conditions was simulated, and the result demonstrated that the fertilization error was controlled within $\pm10\%$. Although spreading uniformity was increased to an extent, the designed device simultaneously realized the horizontal, longitudinal, and inclined adjustments and rotating control, thus increasing structural complexities and control difficulties. Chinese scholars mainly focus on disc, cone disc, grooved wheel, and helix spreaders. Zhang et al. [21] designed a chain conveying variable applicator on the basis of prescription map and analyzed the movement and stresses of fertilizer particles on tri-blade discs. They also created key components and control systems, such as conveying chain and spreading disc. The C_V of the effective width reached 14.9%. Yang et al. [22] designed a five-blade centrifugal disc spreader and discussed the influences of its advancing speed, rotating speed, and the rotating speed of chain plate on the C_V of spreading uniformity, width, and amount of fertilization. They revealed that the minimum C_V was 10.2%. Pan et al. [23] presented a theoretical design and performed a simulation analysis on the movement trails of fertilizer particles on a horizontal round disc. Moreover, the rotating speed of spreading disc and installation position of blades conducted a bench test to achieve the best spreading uniformity. However, parameters for uniformity measurement were not provided. Hu et al. [24] constructed a relationship model of advancing speed, number of blades on the centrifugal disc, and biased angle of blades. They also determined the influencing order of these factors. The minimum distribution C_V was 6.12%, and an experimental verification was performed. Shi et al. [25] verified the blade structure size, rotating speed of disc, distance between the centers of two discs, and installation position of blades on a horizontal two-disc organic fertilizer distributor through an orthogonal test. However, they only measured the spreading uniformity with the changes of mean variation. Lu et al. [26] developed a centrifugal two-disc spreader, and designed its transmission system, disc structure, and flow adjustment device. The C_V of spreading uniformity under the best parameters was lower than 16%. Certain researchers have also investigated the parameters of cone disc and helix spreaders through theoretical calculation and simulation to increase spreading uniformity [27-29]. Chinese studies on the existing spreading mechanism involve various parameters and their optimization. The C_V of the disc spreader is higher than 6%. On the other hand, without considering advancing speed, the minimum C_V of the horizontal spreading of the cone disc spreader can reach 5.8%. On the basis of grain cleaning structure, a sieve bucket spreading mechanism, along with its key parameters, was designed in this study to further increase spreading uniformity. The performance of the proposed mechanism was analyzed. The conclusions in this study can serve as references to further increase spreading uniformity and accuracy.

The remainder of this study is organized as follows. Section 3 presents the design, modeling, and simulation of the sieve bucket spreader. Section 4 discusses the performance of the sieve bucket spreader under different structural parameters. Section 5 summarizes the conclusions.

3. Methodology

3.1 Model of helix grooved wheel fertilizer system

The helix grooved wheel fertilizer system is mainly composed of fertilizer tank, helix grooved wheel apparatus, and sieve bucket spreading mechanism (Fig. 1). Except for the helix grooved wheel apparatus, the sieve bucket spreading mechanism is also an important influencing factor of spreading uniformity. In this study, a sieve bucket spreading mechanism was designed, and its performance under different parameters was examined using the EDEM.



1. Fertilizer tank 2. Helix grooved wheel apparatus 3. Sieve bucket spreading mechanism 4. Draft gear 5. Reducer 6. Servo motor 7. Rack 8. Land wheel

Fig. 1. Structure of helix grooved wheel spreader

The helix grooved wheel apparatus begins to fertilize at a certain rotating speed. As fertilizers fall in the sieve bucket, the spreading mechanism begins to swing at a certain angle and frequency, and the fertilizers are discharged through the hole.

3.2 Determination of the key parameters of the sieve bucket spreading mechanism

The sieve bucket spreading mechanism is a crank and rocker mechanism, whereas the spreading tank is the rocker of the mechanism. To ensure that the fertilizers do not overflow from the upper position as the spreading tank swings, two extreme swinging positions are determined according to the position of outlet on the apparatus and movement state of fertilizers in the spreading tank.

3.2.1 Determination of the overall size parameters of different components

The three relative positions (left-most, moderate, and right-most) between driving member AB and rocker CD are known as α_1, α_2, and α_3 and β_1, β_2, and β_3, respectively. On this basis, the lengths of different components are determined, and the relevant size parameters of the spreading mechanism are set.

Coordinate system xAy is constructed (Fig. 2), where α_0 is the initial angle; *a*, *b*, *c*, and *d* are the lengths of different components; and α_0 and β_0 are the initial angles of AB and CD, respectively.

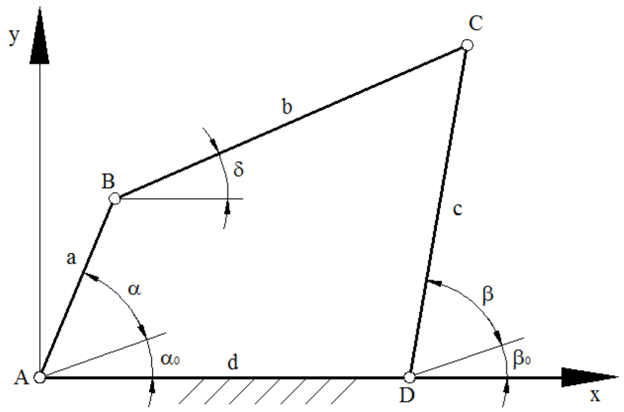


Fig. 2. Design of the sieve bucket spreading mechanism (based on analytical method)

The projections of different components were made on x-axis and y-axis as follows:

$$a\cos(\alpha+\alpha_0)+b\cos\delta=d+c\cos(\beta+\beta_0) \quad (1)$$

$$a\sin(\alpha+\alpha_0)+b\sin\delta=c\sin(\beta+\beta_0) \quad (2)$$

The relative lengths $a/a=1$, $b/a=m$, $c/a=n$, and $d/a=p$ were included in Equation. (1) and (2), thus obtaining the following.

$$\cos(\alpha+\alpha_0)$$

$$=n\cos(\beta+\beta_0)-(n/p)\cos[(\beta+\beta_0)-(\alpha+\alpha_0)]+(p^2+n^2+1-m^2)/2p, \quad (3)$$

Where $R_1=n$, $R_2=-n/p$, and

$R_3=(p^2+n^2+1-m^2)/2p$.

When $\alpha_0=\beta_0$,

$$cos\alpha=R_1\cos\beta+R_2\cos(\beta-\alpha)+R_3 \quad (4)$$

Three groups of positional angles (α_1, β_1, α_2, β_2 α_3 and β_3) were inserted into Equation. (4) to calculate the lengths of different components. On this basis, the main structural parameters of different components of the spreading mechanism were determined.

3.2.2 Determination of the keyhole size of the fertilizer spreading mechanism

Fertilizer discharging holes are set at the bottom and rear positions of the spreading tank. The structural parameters of the holes can determine if the fertilizers can be successfully discharged from the holes.

(1). Size of holes

We define *r* as the ratio between the length of holes and the half of the fertilizer particle's size. $r=4\text{-}5$, and $r=c/(b/2)$. That is, $c=(2\text{-}2.5)b$. where b is the length of fertilizer particles, and c is the hole size. In this study, $r=4$, and the fertilizer particle size and hole size meet this relationship.

(2). Distribution height of holes

Fertilizer particles have three movements when they are discharged from the apparatus to the spreading mechanism. First, the fertilizer particles are spread directly from holes. Second, the particles are discharged after repeated movement at the bottom of the tank. Last, the particles are discharged as they rise along the rear position of the spreader. The distribution height of holes at the rear position mainly determined by the third movement. The stresses on the fertilizers during rear rising are illustrated in Fig. 3

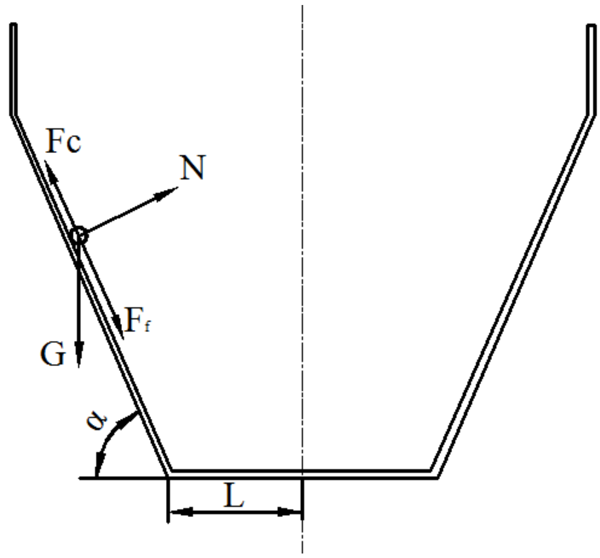


Fig. 3. Stresses on the fertilizer particles in the spreading tank

$$\begin{cases} F_c-F_f-G\cos\alpha=0 \\ N-Gsin\alpha=0 \\ G(\dfrac{h}{\cos\alpha}+L)+F_fL\sin\alpha-F_cLsin\alpha-N(h+L\cos\alpha)=0 \end{cases} \quad (5)$$

On the basis of Equation. (5), the distribution height (h) of holes in the rear position of the spreading mechanism can be calculated as follows:

$$h = \frac{2L\cos a(\sin 2\alpha - 1)}{2 - \sin 2\alpha} \quad (6)$$

where F_c is the inertia force, F_f is the force of friction between fertilizers and the spreader, G is the self-gravity of fertilizer particles, N is the supporting force of fertilizer particles, h is the height of holes, L is half the width of the spreading tank's bottom, and α is the dip angle of the mechanism's front and rear tank surfaces.

3.3 Simulation analysis on the performance of the sieve bucket spreading mechanism

3.3.1 Modeling

The sieve bucket spreading mechanism is mainly composed of driving member (1) (crank circle), connecting rod (2), spreading tank (3) and rack (4). The structure is illustrated in Fig. 4.

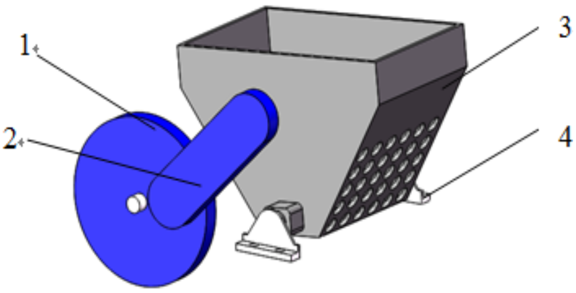


Fig. 4. Model of the sieve bucket spreading mechanism

3.3.2 Determination of parameters

In the simulation analysis, the material parameters and contact mechanical parameters among different materials in the test system were obtained through measurements and literature review [30-32]. The simulation parameters are listed in Table 1.

Table 1. Simulation parameters

Attribute	Parameters	Values
Fertilizer	Particle size $d/(mm)$	2.97
	Density $(\rho / kg.m^{-3})$	1333
	Poisson's ratio v	0.25
	Elasticity modulus $G/(Pa)$	9.2×10^6
Spreading tank	Density $(\rho / kg.m^{-3})$	7850
	Poisson's ratio v	0.24
	Elasticity modulus $G/(Pa)$	196
Interaction	Static friction coefficient between fertilizer and spreading tank μ_1	0.278
	Dynamic friction coefficient between fertilizer and spreading tank v_1	0.152
	Static friction coefficient between fertilizer μ_2	0.906
	Dynamic friction coefficient between fertilizers v_2	0.495
	Dynamic friction coefficient between fertilizer and surface v_3	1.22
Others	Gravity $g/(m/s^2)$	9.8

3.3.3 Simulation process and experimental design determination of parameters

The different structures of the sieve bucket spreading mechanism were inputted into the discrete element simulation software. Relevant parameters were set to verify the mechanism performance. A simulation surface was set (length x width = $800mm \times 1000mm$) below the sieve bucket spreading mechanism. The surface moved at different speeds along actual directions after 0.2 s. Then, the grid bin group was longitudinally set (Y direction) on the surface by using the EDEM post-processing selection module. Each grid size was $600mm \times 800mm$ (Fig. 5). A particle factory was set, and the fertilizer particles were installed into the tank during the simulation. Finally, the kinetic characteristic parameters of the assembly were set. The fertilizer apparatus began to spread fertilizer particles at a certain rotating speed, whereas the relevant parameters were adjusted. The total simulation time was $4s$. The simulation effect of the sieve bucket spreading mechanism is exhibited in Fig. 5.

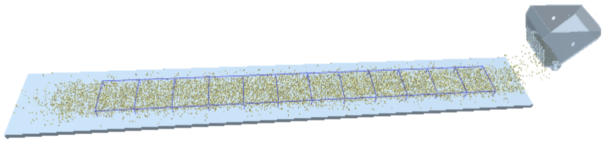


Fig. 5. Simulation effect of the sieve bucket spreading mechanism

3.3.4 Spreading uniformity evaluation

Spreading uniformity is an important index to evaluate the performance of fertilizer applicators, which are measured by C_V. Small C_V signifies good fertilization consistency and uniformity. C_V is expressed as follows:

$$C_V = \frac{SD}{\overline{m}} \quad (7)$$

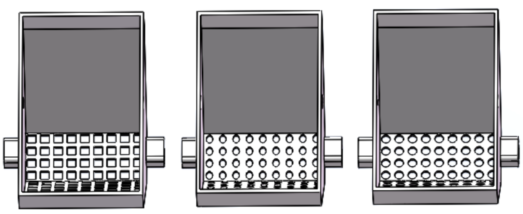
$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(m_i - \overline{m})^2} \quad (8)$$

where SD is the standard deviation, and $\overline{m}$ is the absolute mean of fertilizer mass (g).

4. Results analysis and discussion

4.1 Effects of hole shape on spreading uniformity

Given the same parameters, three different structures of sieve bucket spreading mechanisms were applied to compare their spreading performances (Fig. 6). The basic sizes were (1) square hole ($a = 4\,mm$), (2) circular hole ($\phi 4\,mm$), and (3) elliptical hole ($2a = 4\,mm$). The fertilizer distributions under three different hole shapes are presented in Fig. 5.



(a) square hole (b) elliptical hole (c) circular hole

Fig. 6. Structures of the sieve bucket spreading mechanism

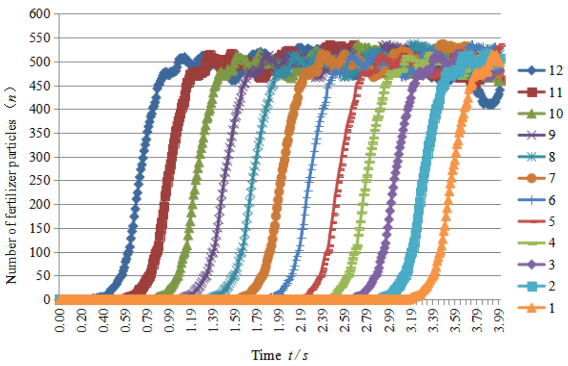


Fig. 7(a). Spreading performance of the sieve bucket spreading mechanism with square holes

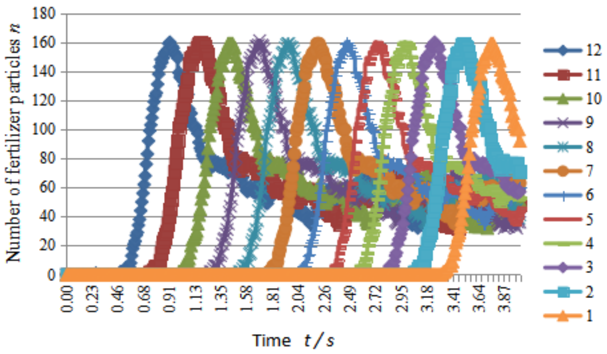


Fig. 7(b). Spreading performance of the sieve bucket spreading mechanism with elliptical holes

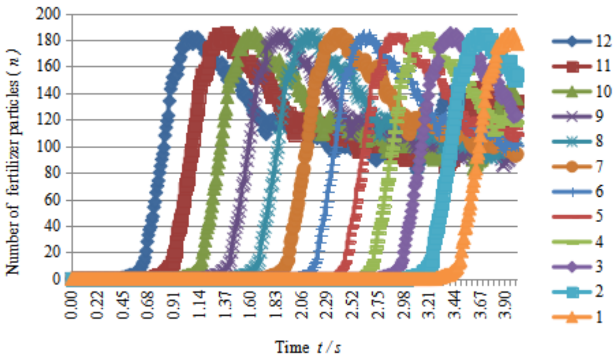


Fig. 7(c). Spreading performance of the sieve bucket spreading mechanism with circular holes

Fig. 7 illustrates that given the same time, the sieve bucket spreading mechanism with square holes discharges the most fertilizer particles, followed by the spreading mechanism with circular holes and that with elliptical holes. Fig. 8 reveals that the maximum and minimum C_V of the sieve bucket spreading mechanism with square holes are 3.68% and 1.14%, respectively, with an average value of 2.46%. For the mechanism with circular holes, the maximum and minimum C_V are 10.17% and 3.15%, respectively, and the average is 5.43%. The maximum and minimum C_V of the mechanism with elliptical holes are 16.38% and 4.29%, respectively, averaging at 8.93%. The spreader with square holes obtains the lowest average C_V, followed by the mechanism with circular holes, and then the spreader with elliptical holes. In conclusion, the sieve bucket spreading mechanism with square holes exhibits the best spreading uniformity among the three.

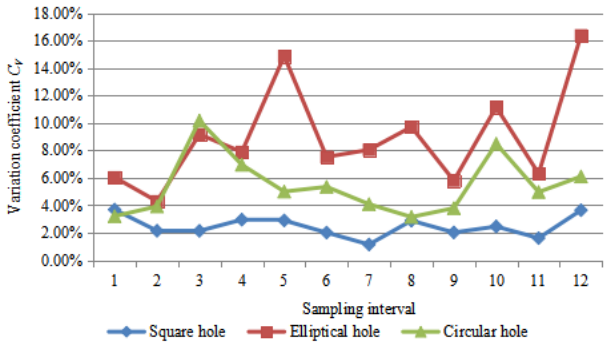


Fig. 8. Comparison of C_V under different structures

4.2 Effects of hole distance on spreading uniformity

Although the sieve bucket spreading mechanism with square holes achieves the best spreading uniformity, fertilizer particles may be blocked in the spreading tank. Therefore,the structural parameters of this mechanism must be optimized to ensure that fertilizers can be smoothlydischarged through the spreader.The relationship between k and the amount of fertilizer discharge and the coefficient of variation of spreading fertilizer is studied, as shown in Figs. 9 and 10 (where k is the ratio between hole distance and hole size).

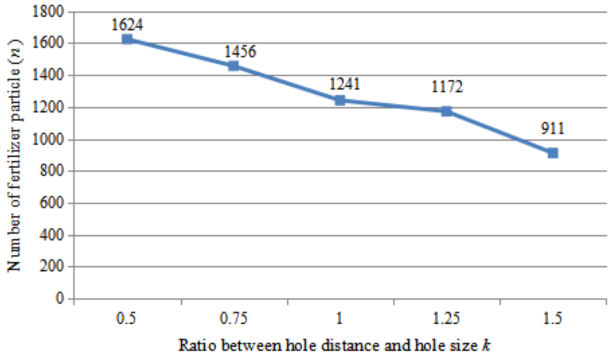


Fig. 9. Spreading amount under different hole distances

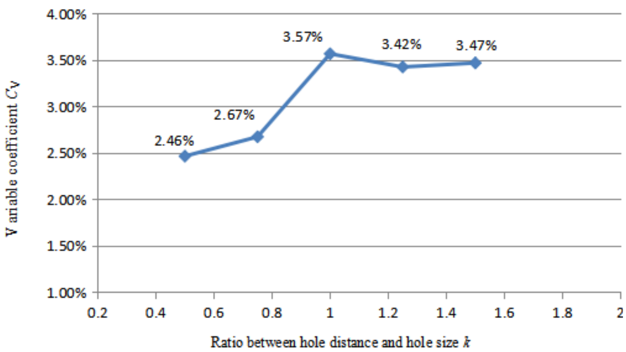


Fig. 10. C_V under different hole distances

Fig. 9 shows that given the same conditions, the number of spreading fertilizer particles decreases as k increases. A total of 1,624 particles exists when $k=0.5$ but decreases to 1,546 when $k=0.75$, 1,241 when $k=1$, 1,172 when $k=1.25$, and 911 particles when $k=1.5$. Fertilizers can be spread smoothly without accumulation under different values of k. Fig. 10 illustrates that under the same conditions, the C_V of the spreading mechanism is positively related with the value of k. The C_V of this mechanism is 2.46% when $k=0.5$ and further increases to 2.67% when $k=0.75$, 3.57% when

$k=1$, 3.42% when $k=1.25$, and 3.47% when $k=1.5k$. The C_V of spreading ranges between 2.5% and 3.6% and is controlled smaller than 5%, meeting the requirements of uniform spreading. Therefore, under the same conditions, the number of fertilizer particles greatly changes as the ratio between hole distance and hole size increases, but the C_V of spreading is controlled lower than 4%. As a result, the ratio between distance and the hole size of the spreading mechanism slightly influences spreading uniformity under the same conditions.

4.3 Effects of advancing speed on spreading uniformity

In studying the effects of the structural parameters of holes on spreading uniformity, the ratio between hole distance and hole size slightly influences such uniformity. Hence, $k=0.5$ and $k=1.5$ are selected in the comparative study.

Fig. 11 demonstrates that the variable coefficient in the whole sampling interval is controlled within 5% when the advancing speed is 0.2 and $0.4\, m/s$ with small fluctuations. When the advancing speed increases to $0.6\, m/s$, the C_V in the first three sampling intervals greatly changes and becomes controlled within 10% from the fourth sampling interval. When the advancing speed is $0.8\, m/s$ - $1.2\, m/s$, C_V changes between 15% and 35%. Fig. 12 illustrates that as the advancing speed increases, the average C_V of spreading increases continuously and spreading uniformity declines, indicating that the advancing speed influences the C_V of spreading when $k=0.5$

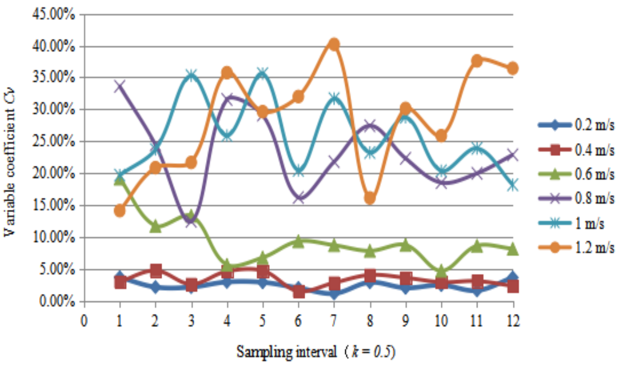


Fig. 11. C_V under different advancing speed ($k=0.5$)

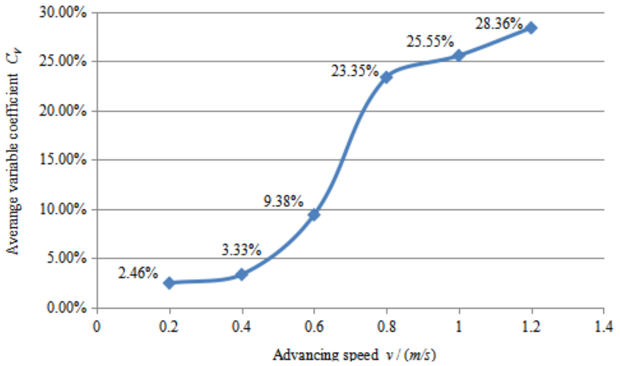


Fig. 12. Average C_V under different advancing speed ($k=0.5$)

Fig. 13 shows that the C_V in the whole sampling interval is lower than 5% and slightly fluctuates when the advancing speed is $0.2\, m/s$. C_V is kept at approximately 5% when the advancing speed increases to $0.4\, m/s$. In the first three sampling intervals, C_V greatly varies at an advancing speed of $0.6\, m/s$ but stabilizes in the other sampling intervals (approximately 10%). C_V ranges between 15% and 35% in the advancing speed range of $0.8\, m/s$-$1.2\, m/s$. In addition, C_V fluctuates within 10% - 45% when the advancing speed reaches $1.4\, m/s$ before any evident changes.

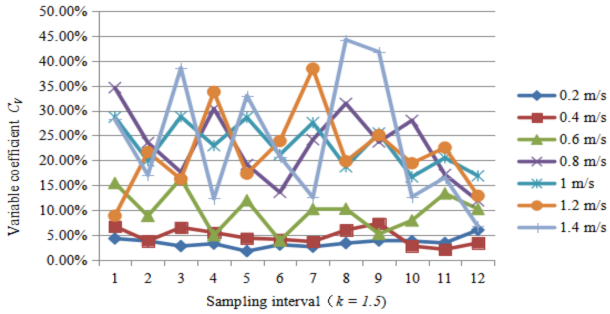


Fig. 13. C_V under different advancing speed ($k=1.5$)

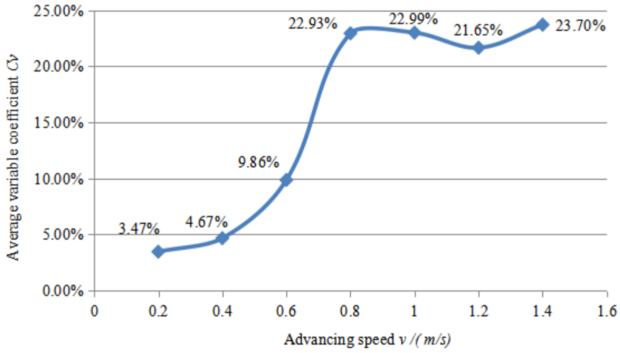


Fig. 14. Variation law of the average C_V of spreading with advancing speed ($k=1.5$)

Fig. 14 illustrates that as the advancing speed increases, the average C_V of spreading increases continuously. After the advancing speed exceeds $0.8\, m/s$, the average C_V initially decreases and then increases, whereas spreading uniformity declines. This result implies that the advancing speed greatly influences C_V when $k=1.5$.

5. Conclusions

To further increase the spreading uniformity, key parameters of the designed sieve bucket spreading mechanism are created then optimized. The performance of this mechanism is discussed using DEM. The conclusions are enumerated below.

(1) Given the same conditions, the sieve bucket spreading mechanism with square holes shows the minimum C_V and the best spreading uniformity among the spreaders with elliptical and circular holes.

(2) Considering the fixed shape of the sieve bucket spreading mechanism with square holes, C_V continuously increases as the ratio between hole distance and hole size increases, accompanied with deteriorating spreading uniformity.

(3) Given the fixed ratio between the hole distance and hole size of the sieve bucket spreading mechanism, C_V generally increases as advancing speed increases. Controlling the advancing speed of the applicator is necessary to ensure fertilization uniformity.

These conclusions can effectively increase the spreading uniformity of solid fertilizers and provide references for future studies on mechanical structure to improve spreading uniformity and accuracy. On the basis of the theoretical design, the performance of the sieve bucket spreading mechanism is investigated using DEM. However, the designed sieve bucket spreading mechanism must be further optimized through additional experiments and examined in actual practices to complete tits actual promotion and application.

Acknowledgments

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