IMPROVEMENT DESIGN AND SIMULATION ANALYSIS ON CENTRIFUGAL DISC ORGANIC FERTILIZER SPREADER
/
离心圆盘式有机肥撒施机改进设计与仿真分析

Bing XU [1,2], Qingliang CUI *[1,2], Decong ZHENG [1,2]
[1)] College of Agricultural Engineering, Shanxi Agricultural University, Taigu 030801 / China;
[2)] Dryland Farm Machinery Key Technology and Equipment Key Laboratory of Shanxi Province, Taigu 030801 / China
Tel: +86-0354-6288339; E-mail: qlcui@126.com
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ABSTRACT
Aiming at the poor efficiency in crushing a handful of caking organic fertilizers spraying from the traditional disc spreader, an improved disc spreader equipped with spike-tooth crushing unit was designed with the introduction of its structural composition and working principle. Also simulation experiments were carried out based on the discrete element method according to the solutions made before and after the structural improvement. Firstly, a granular organic fertilizer model was established based on the EDEM and a caking organic fertilizer bonding model was built based on the HMB (Hertz-Mindlin with bonding) contact model. Then two organic fertilizer spreading models corresponding to the solutions were respectively established, based on which simulation experiments were repeated three times on the spreading process. The analysis on the particle velocity vector diagram revealed the interaction relationship between organic fertilizers with the toothed shaft, external wall and disk, verifying the crushing mechanism of crushing unit. By calculating the total number of the bonds generated and broken in the spreading process in both of the spreading models, the average broken rate of bonds in the spreading process was separately 58.87% and 98.05% based on each solution, revealing that the improved solution outperformed the traditional solution in terms of the efficiency in crushing the caking organic fertilizers. This research will be a reference in designing the critical components or improving the overall performance of disc spreader.

摘要
针对传统圆盘式撒施机在撒施有少量结块的有机肥时，对块状有机肥破碎效果差的问题，改进设计了一种带有钉齿式破碎装置的圆盘式撒施机，阐述了其结构组成和工作原理。基于离散元法对结构改进前、后的两种方案开展模拟试验，首先用 EDEM 软件建立粒状有机肥模型，以 Hertz-Mindlin with bonding（HMB）接触模型为基础建立块状有机肥粘结模型，然后分别建立两种方案对应的有机肥撒施模型，并对撒施过程进行三次重复模拟试验。通过对颗粒运动速度矢量图的分析，明晰了有机肥与钉齿轴、外壁、圆盘之间的作用关系，验证了破碎装置的破碎机理；通过统计两种撒施模型在撒施过程中粘结键生成总数及断裂数，计算得出两种方案在撒施过程中粘结键平均断裂率分别为 58.87%、98.05%，表明改进后的方案对块状有机肥的破碎效果优于传统方案。本研究可为圆盘式撒施机关键部件设计及整机性能提升提供参考。

INTRODUCTION
As an important part in agricultural production, fertilization provides nutrients necessary for crop growth to accelerate the growth and development. The commonly used fertilizers include chemical and organic fertilizers. In recent years, the overuse of fertilizers have led to many problems, such as soil hardening, air and water source pollution, which have become more and more serious. Hence it is very necessary and pressing to apply less fertilizer *(Ma et al., 2019; Wen et al., 2023)*. Researches have shown that organic fertilizer can efficiently improve and increase soil fertility with less environmental pollution, it is a necessity in developing green agriculture *(Sun et al., 2019)*. Therefore, scientifically reduced application of fertilizer and reasonable application of organic fertilizers have become an important approach to improve the quality of cultivated land, increase crop yield and enhance the quality of agricultural products *(Du et al., 2020; Jiang et al., 2023; Fang et al., 2021)*.

[1] *As Lec .M.S.Eng.Bing XU; Qingliang CUI, Prof. Ph.D. Eng.; Decong ZHENG, Prof. Eng.*

Due to the strong bonding force, easy caking and poor fluidity between organic fertilizer granules, organic fertilizer can hardly be spread and this is also one of the main reasons for the low usage of it *(Li et al., 2022)*. As the premise for the wide application of organic fertilizer is the availability of a spreading device with excellent crushing performance, even spreading and high efficiency, the study on an efficient spreading device with good performance is of great significance to accelerate the development of green agriculture.

Currently, according to the different structures, spreaders can be classified into different types, including hammer-shape, roll-type and centrifugal disc spreaders in domestic and overseas market for the spreading of organic fertilizers with different physical properties *(Xu et al., 2022)*. Numerous researches have been made by scholars at home and abroad on the key technologies, such as the structural design of spreader components and the optimization of working parameters during the spreading of organic fertilizers. By taking MG5 organic fertilizer spreader as the research object, Ștefan et al. established a regression model covering the effective working width, effective working quota, rotor speed, conveyor flow, the angle of inclination of the rotors and density of scattered material after the experiment *(Ștefan et al., 2019; Cârdei et al., 2019)*.

Aiming at the problem of poor crushing effect during the spreading of organic fertilizers with high viscosity by traditional spreaders, Lv et al designed a vertical screw spreader with the optimization of structure and working parameters based on the experimental indexes of spreading uniformity and working width *(Lv et al., 2020)*. Based on the discrete element method, Zinkevičienė R et al. built a centrifugal spreading model for cylindrical granular organic fertilizers to evaluate the lateral uniformity of fertilizers over field *(Zinkevičienė et al., 2021)*. In order to increase the uniformity of lateral spreading by organic fertilizer spreader, Liu et al. managed to control the shape of jet flow by innovating the components and optimizing the structural parameters based on the quantitative representation of the shape of jet flow from the spreading device *(Liu et al., 2022)*. Wu et al. designed a spreading device for organic fertilizer spreader by selecting the number of spiral lines on the spreader roll, the screw pitch of blade, the blade angle and the rotation speed as the experimental factors. In the field experiment made based on the variable coefficient of fertilization, which had also served as an evaluation index, the optimal combination of parameters for the spreader roll was obtained *(Wu et al., 2022)*.

Generally, due to the excellent crushing performance, crushing roll-type spreader is applicable to the spreading of barnyard manure that is of high humidity in block structure. With great working width, centrifugal disc spreader is applicable to the spreading of granular or powdered organic fertilizer due to the poor crushing effect. When it is used for the spreading of organic fertilizers, among which most of them are powdery or granular with the mixture of a small number of caking organic fertilizers, the spreading effect will be affected as the caking fertilizers can hardly be crushed efficiently. In view of this, a centrifugal disc spreader equipped with crushing unit was designed in this paper after the structural improvement based on the traditional disc spreader. Also based on the discrete element method, two organic fertilizer spreaders were separately built before and after the structural improvement. Through numerical simulation, both of the solutions had been compared in terms of the crushing of caking organic fertilizers during the operation with an aim to provide a reference to improve the overall performance of spreader.

MATERIALS AND METHODS

Structural composition and principle of disc spreader

In traditional disc spreader, spreading disk serves as the main working component during the operation. Fertilizers have been conveyed backward to the spreading disk via the chain conveying unit and the high-speed rotation of spreading disk contributes to the even spreading of fertilizers to the field. It is applicable to the spreading of powdery or granular fertilizers *(Ma et al., 2019)*.

However for the spreading of a handful of caking organic fertilizers, it doesn't work efficiently in crushing them. Therefore a centrifugal disc spreader equipped with crushing unit has been designed after the structural improvement based on the traditional disc spreader.

As indicated in Figure 1, it mainly consists of traction frame, chain conveying unit, toothed crushing unit, disc spreading unit and universal drive shaft. It is driven by the tractor, whose conveyor driven shaft drives the disk to rotate via the universal drive shaft. During the operation, firstly the organic fertilizers in the fertilizer box will be conveyed to the crushing unit for crushing via the chain conveying unit and then be spread to the field through the disc spreading unit after the crushing.

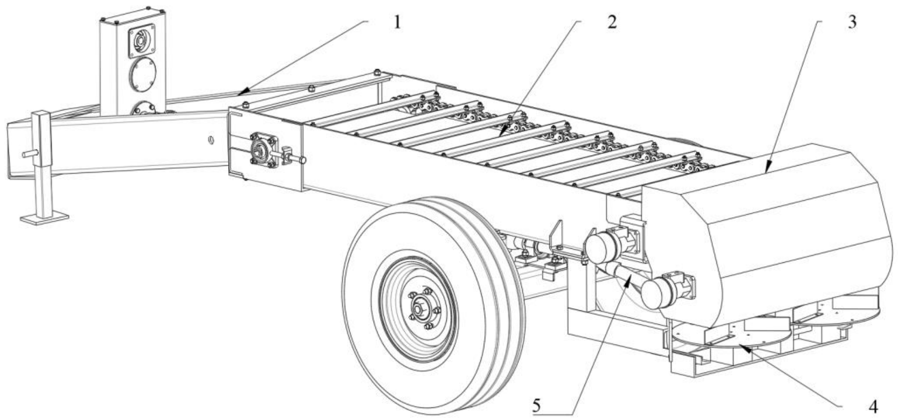
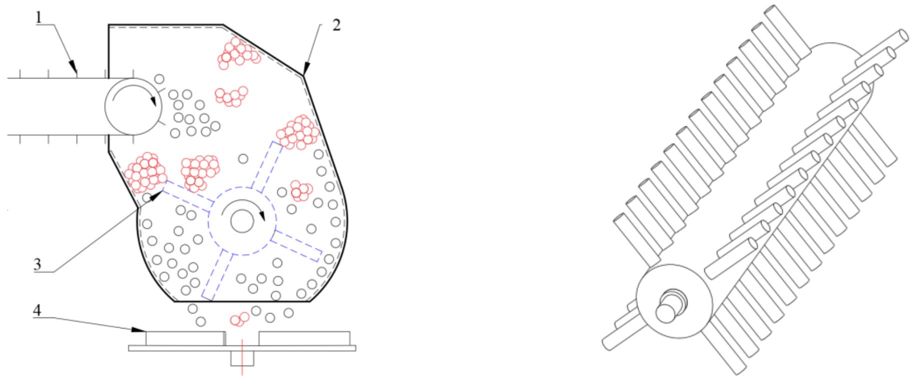


Fig. 1 - Structural composition of disc spreader equipped with crushing unit
1- traction frame; 2- chain conveying unit; 3- toothed crushing unit; 4- disc spreading unit; 5- universal drive shaft

As shown in Figure 2(a) and (b), the spike-tooth crushing unit mainly consists of toothed shaft and external wall. During the operation, organic fertilizers will be conveyed via the chain conveying unit to the inlet of the crushing unit, where the organic fertilizers with smaller particle size will drop to the outlet through the gaps between the spike teeth or between the teeth and the external wall. However, the caking organic fertilizers with larger particle size won't pass directly through the gaps and most of them will interact with the spike teeth and the external wall in the crushing unit with the high-speed rotation of the toothed shaft. They will be broken up due to the impact, collision and squeezing effect and a handful of organic fertilizers will be crushed when they collide with the disk at high speed due to the acceleration effect of the toothed shaft.



（a）Schematic diagram of crushing unit （b）toothed shaft

Fig. 2 - Structural composition and principle of toothed crushing unit
1- chain conveying unit; 2- external wall; 3- toothed shaft; 4- disk

Construction of discrete element model

Construction of organic fertilizer model

Based on the EDEM software, granular and caking organic fertilizer models were separately built, among which the granular model was constituted by various spheroidal particles in a radius of 8 mm, as shown in Figure 3(a), while the caking fertilizer model that was built based on the HMB (Hertz-Mindlin with bonding) contact model was constructed through the bonding of several above-mentioned spheroidal particles through the bonds. The main factors affecting the bonds include the normal stiffness per unit area, shear stiffness per unit area, critical normal stress, critical shear stress and bonded disk radius *(Wang et al., 2010)*. The bonds can work under a certain normal force or tangential force, but they will break when the outside force exceeds the critical stress of bonds and then the block-shaped particles will be broken into some smaller blocky particles or spheroidal particles. Due to the caking, the organic fertilizers vary in shape and size. Hence in order to simplify the modeling process, only a type of caking organic fertilizer model was built with the process as below: Firstly, based on the 3D modeling software, a 3D caking organic fertilizer model was constructed, which was also introduced into the EDEM to serve as the contour of the organic fertilizer. Then based on the HMB contact model, the spheroidal particles with a radius of 8 mm made a full profile with the setting of bonding parameter to generate the bonds. With reference to the literature, the bonded disk radius was generally 1.2~2 times the radius of particles *(Li et al., 2021)*.

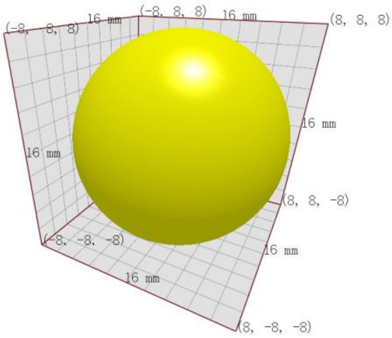
In this paper, it is set to be 10 mm. In order to verify the efficiency in crushing the organic fertilizers based on the improved solution to cater for the crushing and spreading of the organic fertilizers with different bonding forces, the values of the HMB bonding parameters were properly increased based on the existing researches *(Wu, 2016)* in terms of the critical normal stress and critical shear stress, as shown in Table 1.

Table 1

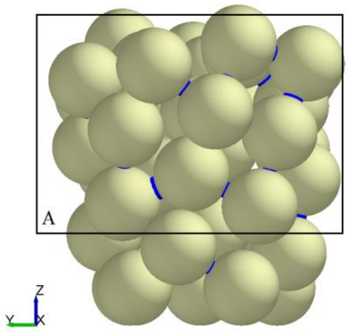
Bonding parameters of HMB

Parameters	Values
Normal stiffness per unit area	1×10^{8} N/m^{-3}
Shear stiffness per unit area	5×10^{7} N/m^{-3}
Critical normal stress	0.55 MPa
Critical shear stress	0.55 MPa
Bonded disk radius	10 mm

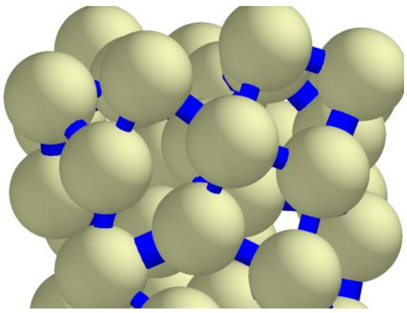
Figure 3(b) and (c) showed the caking organic fertilizer bonding model, where every caking model consisted of 40 spheroidal particles and 100 bonds. Figure 3 (d) showed the distribution of the bonds within the caking model. Finally, the position of every spheroidal particle within the caking model was exported and saved as the particle template.



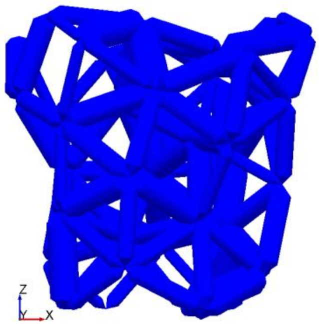
(a) granular organic fertilizer model



(b) caking organic fertilizer model



(c) partial enlarged view of area A in Figure 3 (b)



(d) distribution of the bonds within the caking model

Fig. 3 - Discrete element model of organic fertilizer

Construction of organic fertilizer spreading model

Two organic fertilizer spreading models before and after the structural improvement of spreader were separately built based on the discrete element method. Through numerical simulation, both of the structural solutions were compared and analysed in terms of the efficiency in crushing organic fertilizers. But during the construction of both spreading models, none of them were built with the modelling of conveying unit. The organic fertilizer spreading model equipped with crushing unit was constructed according to the following process: Based on the 3D modelling software, the 3D models for the spreading unit and the crushing unit were built, which then were saved in stp format and exported into the EDEM. After referring to the design manual *(China Academy of Agricultural Mechanization Sciences, 2007)*, the rotation speed of disk was set to be 540 r/min and 1200 r/min for the toothed shaft. As provided in Table 2 and 3, the intrinsic parameters and the contact parameters of the materials involved in the spreading model had been set according to the relevant references *(Li et al., 2022; Liu et al., 2022; Wu, 2016)* and combining simulation practice.

Table 2

Material intrinsic parameters

Material	Poisson's ratio	Shear modulus/Pa	Density/（kg·m^{-3}）
Organic fertilizer	0.315	5.5×10^{6}	1.25×10^{3}
Steel	0.30	7.90×10^{10}	7.90×10^{3}
Soil	0.3	5×10^{7}	2.60×10^{3}

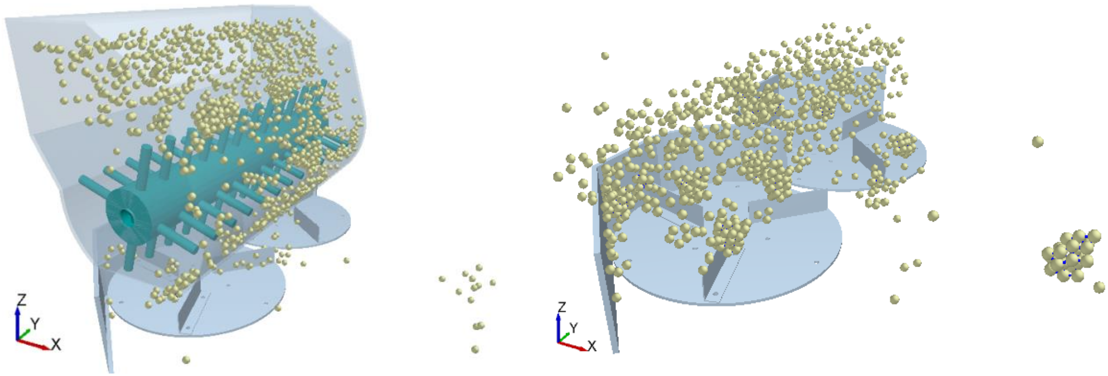
Table 3

Material contact parameters

Material	Restore collision coefficient	Static friction coefficient	Rolling friction coefficient
Organic fertilizer -Organic fertilizer	0.01	1.2	1
Organic fertilizer-Steel	0.01	0.5	0.5
Organic fertilizer-Soil	0.01	0.8	0.6

Particle factory was set up at the inlet of the crushing unit to simulate the conveying of the granular organic fertilizer via the conveying unit. In the particle factory, two particle models separately for granular and caking organic fertilizers were generated, among which the granular model was generated at the moment of 0.05 s and lasted to the end of the simulation at a generating rate of 3000 s.

The caking fertilizer model was generated as follows. Firstly, 15 spheroidal particles with a radius of 40 mm were generated in the period of 0~0.05 s within the particle factory. After reading the data of the particle templates from the caking fertilizer model via the EDEM API at the moment of 0.052 s, the spheroidal particles with a radius of 40 mm were replaced by the block-shaped particles. The initial velocity of both particles was 0.1 m/s in the direction of the negative Z-axis. Figure 4(a) showed the organic fertilizer spreading model equipped with crushing unit, while Figure 4(b) showed the traditional centrifugal disc spreading model established in the same way.



（a）organic fertilizer spreading model equipped with crushing unit （b）traditional centrifugal disc spreading model

Fig. 4 - Organic fertilizer spreading model

Numerical simulation and post-processing method

Simulation experiments on both spreading models were separately repeated three times with the simulation duration set to be 1 s, and data had been saved every 0.01 s.

In order to specify the interaction relationship between the organic fertilizer with the toothed shaft, the external wall and the disk in the improved spreading model, the velocity vector diagram of the granules moving at different moments was exported to observe the velocity vector direction of the organic fertilizer granules and the motion trend in the crushing unit to explore the crushing mechanism of the unit. To facilitate the quantitative analysis on the effect of crushing organic fertilizers in both spreading models during the spreading process, the total number of the bonds generated at the beginning of the simulation and the number of the bonds broken at the end of the simulation were calculated and then the average broken rate of the bonds was separately calculated in each spreading models.

RESULTS

After the simulation, the velocity vector diagram of the granules moving at different moments in the crushing unit was exported in the improved spreading model, as shown in Figure 5, where the direction of arrow, colour and length separately represented the direction of particle velocity, velocity and kinetic energy.

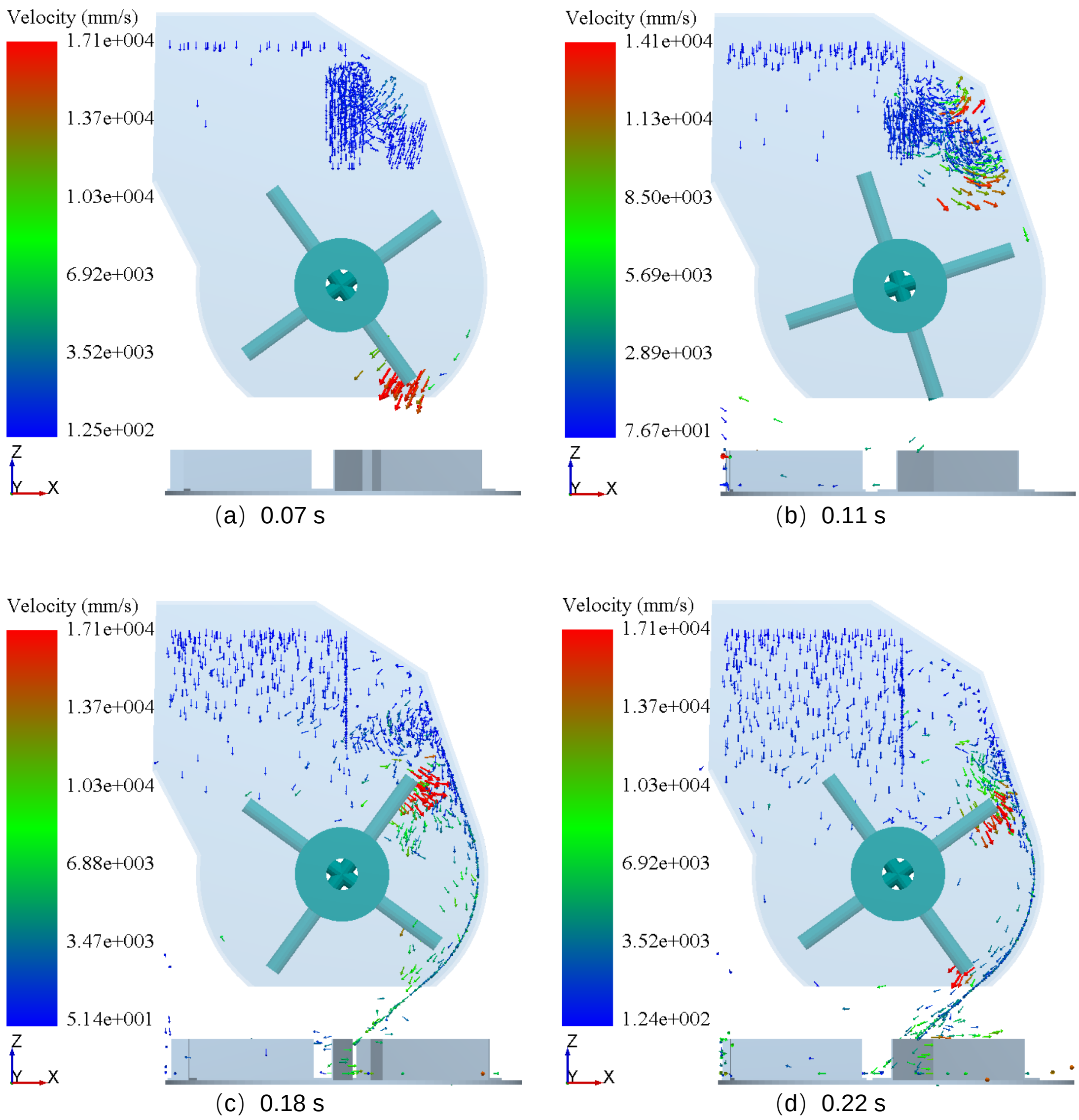
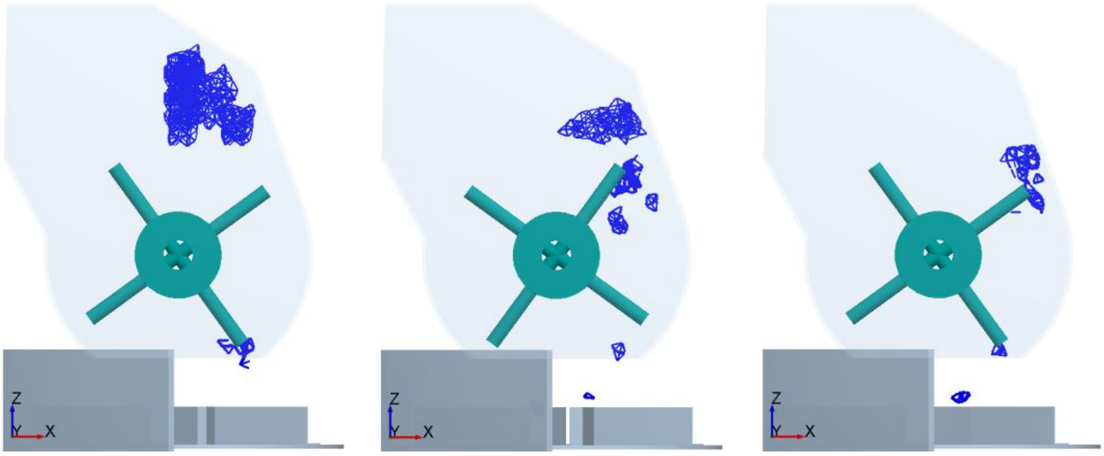


Fig. 5 - The velocity vector diagram of the granules

Figure 5(a) showed that at the outlet of the crushing unit, some granules still moved at high speed towards the disk, indicating the acceleration effect of the toothed shaft on those organic fertilizers that failed to pass through the gap between the teeth.

As shown in Figure 5(b), some granules collided with the external wall at high speed under the acceleration effect of the toothed shaft in the crushing unit. Also Figure 5 (c) and (d) showed the impact and squeezing actions between a handful of granules with the toothed shaft and the external wall. In conclusion, the high-speed collision, impact and squeezing actions between the organic fertilizer and the relevant components in the crushing unit had made a contribution to the crushing of caking organic fertilizers. To observe directly the breakage of the bonds and the crushing process of the block-shaped granules, the distribution variation diagrams of the bonds and the granules at different moments in the crushing unit were exported, as shown in Figures 6 and 7.



(a) 0.07 s (b) 0.18 s (c) 0.22 s

Fig. 6 - The distribution variation diagrams of the bonds

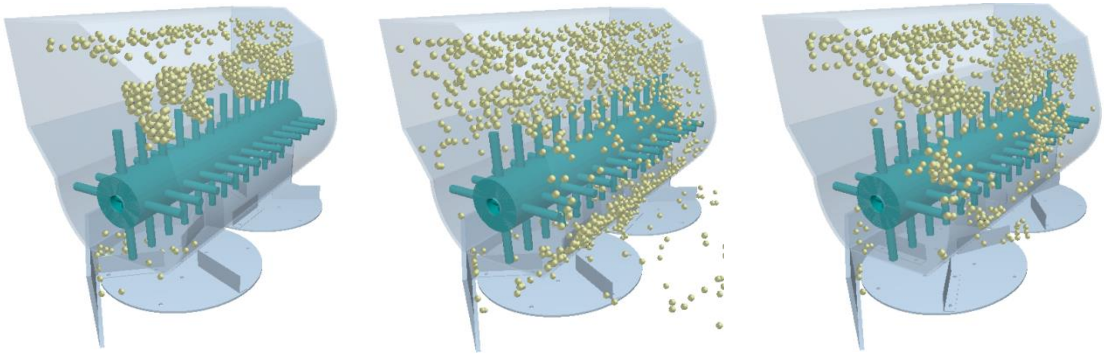
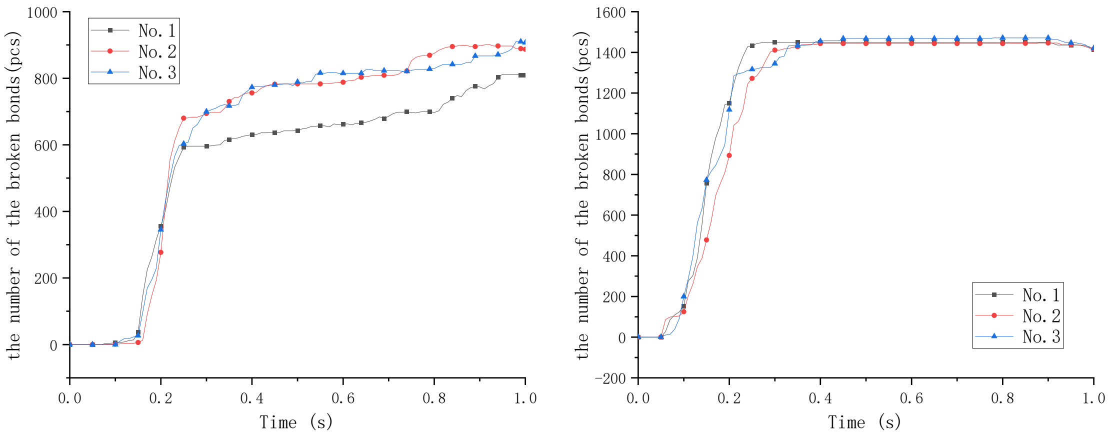

(a) 0.1 s (b) 0.15 s (c) 0.25 s

Fig. 7 - The distribution variation diagrams of the granules

Figures 6 and 7 showed that in the initial stage of the simulation, both of the bonds and the block-shaped granules were relatively intact. But in the period of 0.15~0.18 s, some bonds were broken and the block-shaped granules were crushed into smaller block-shaped particles or spheroidal particles. In the period of 0.22~0.25 s, the bonds were further broken up and the particles were separated into more pieces in smaller granular size.

Figure 8 showed the curves of the changes in the number of the broken bonds over time during the spreading process in each spreading model.



(a) traditional solution (b) improved solution

Fig. 8 - The curves of the changes in the number of the broken bonds over time

As shown in Figure 8, bonds were broken mainly before 0.25 s in both of the spreading models. Also in the experiments that had been repeated several times, the improved solution outperformed the traditional solution regarding the number of the broken bonds.

To facilitate the quantitative evaluation on both solutions in terms of the crushing of organic fertilizers, the total number of the bonds generated in the simulation process and the number of broken bonds at the end of simulation were separately calculated based on each solution to calculate the broken rate of bonds, as indicated in Table 4.

Table 4

Bonds data

solution	No.	total number of bonds/pcs	number of broken bonds/pcs	the broken rate of bonds/%	average value/%
traditional solution	1	1487	812	54.61	58.87
	2	1487	902	60.66	
	3	1485	911	61.35	
improved solution	1	1485	1452	97.78	98.05
	2	1476	1446	97.97	
	3	1495	1471	98.39	

As shown in Table 4, the average broken rate of bonds was separately 58.87% and 98.05% in both spreading models, proving that the improved solution outperformed the traditional solution in terms of the efficiency in crushing caking organic fertilizers.

CONCLUSIONS

(1) Aiming at the poor efficiency in crushing a handful of caking organic fertilizers spraying from the traditional disc spreader, an improved disc spreader equipped with spike-tooth crushing unit was designed with the introduction of its structural composition and working principle.

(2) The organic granular fertilizer model was built based on the EDEM software. Also based on the HMB (Hertz-Mindlin with bonding) contact model, the caking organic fertilizer bonding model and the organic fertilizer spreading models established before and after the structural improvement had been constructed with the running of the numerical simulation.

(3) Based on the analysis on the velocity vector diagram of the granules, the interaction relationship between the organic fertilizers with the toothed shaft, the external wall and the disk as well as the crushing principle were clearly specified. In order to compare the efficiency in crushing organic fertilizers during the spreading process based on both solutions, the total number of the bonds generated and broken in each spreading model was calculated, showing that the average broken rate of the bonds was separately 58.87% and 98.05% after the calculation made based on each solution. It proved that the improved solution was better than the traditional solution in terms of the efficiency in crushing caking organic fertilizers.

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REFERENCES

[1] Cârdei P., Ştefan V., Popa L., Ciuperca R., (2019), Statistical models for the working process carried out by the organic fertilizer spreading machine. *INMATEH Agricultural Engineering*, Vol.58, Issue 2, pp.121-128, Bucharest/Romania.

[2] Du W.Y., Tang S., Wang H., (2020), The status of organic fertilizer industry and organic fertilizer resources in China. *Soil and Fertilizer Sciences in China*, Vol.287, Issue 3, pp.210-219, Beijing / China.

[3] Fang P.P., Abler D., Lin G.H., Sher A., Quan Q., (2021), Substituting Organic Fertilizer for Chemical Fertilizer: Evidence from Apple Growers in China. *Land*, Vol.10, Issue 8:858, Basel/ Switzerland.

[4] Jiang S.T., Li H., Peng H.Y., Mei X.L., Chen T.S., Xu Y.C., Dong C.X., Shen Q.R.,(2023), Effects of partial substitution of chemical fertilizer with organic fertilizer on arbuscular mycorrhizal fungal community of Mangifera indica. *Chinese Journal of Applied Ecology*, Vol.34, Issue 2, pp.481-490, Shenyang / China.

[5] Li J.G., Liu X.M., Zou L.L., Yin R.G., Yang K., Yuan J., (2021), Discrete Element Modeling Method and Experimental Verification of Spinach Main-root. *Journal of Agricultural Mechanization Research*, Vol.43, Issue 08, pp.181-185+191, Harbin/China.

[6] Li L., Cui Q.L., Zhang Y.Q., Hou H.M., Xi P., Hao C., (2022), Experimental Study on Scattering Performance of Organic Fertilizer Spreader Based on EDEM. *Agricultural engineering*, Vol.12, Issue 3, pp.88-94, Beijing / China.

[7] Liu H.X., Du C.L., Yin L.W., Zhang G.F., (2022), Shooting Flow Shape and Control of Organic Fertilizer Side Throwing on Inclined Opposite Discs. *Transactions of the Chinese Society for Agricultural Machinery*, Vol.53, Issue 1, pp.168-177, Beijing / China.

[8] Lyu J.Q., Sun Y.K., Li J.C., Li Z.H., Liu Z.Y., (2020), Design and test of vertical spiral organic fertilizer spreading device. *Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE*), Vol.36, Issue 24, pp.19-28, Beijing / China.

[9] Ma B., Fu J.J., Xu B.X., Wu A.B., Xie H., Chen Y.S., (2019), Research on manure spreader technology and equipment. *Journal of Chinese Agricultural Mechanization*, Vol.40, Issue 08, pp.1-6, Nanjing/China.

[10] Sun D.X., Li M.J., Wu A.B., Liang Q., Zhang A.M., (2019), Research progress of organic fertilizer and its supporting mechanization technology. *Journal of Chinese Agricultural Mechanization*, Vol.40, Issue 02, pp.72-80, Nanjing/China.

[11] Ştefan V., Cârdei P., Popa L., David L., Ciupercă R., (2019), Influence of the manure spreading machines' working parameters on the qualitative performances of the fertilization process. *INMATEH Agricultural Engineering,* Vol.58, Issue 2, pp.115-120, Bucharest/Romania.

[12] Wen C.Y., Xiong Y.H., Wang P. Zhang Z.Y., Yao X.Y., Peng Z.Q., Chen J., Wu Y.S., (2023), Effects of Reduced Chemical Fertilizer with Organic Fertilizer Application on Yield and Quality of High-quality Indica Rice. *Soils*, Vol.55, Issue 02, pp.280-287, Nanjing/China.

[13] Wu H., Liu X.F., Zhang H.B., Chen W.X., (2022), Design and Test of the Spreading Device of Organic Fertilizer Spreader. *Journal of Agricultural Mechanization Research*, Vol.44, Issue 11, pp.113-118, Harbin/China.

[14] Wu N., (2016), *Research and Design of 2F50 Manure Spreader.* Master thesis. Chinese Academy of Agricultural Mechanization Sciences, Beijing/China.

[15] Xu B.X., Chen Y.S., Chen M.J., Ma B., Gao Q.M., Wu A.B.,(2022), Research status and development trend of organic fertilizer application equipment for field crops in China. J*ournal of Chinese Agricultural Mechanization,* Vol.43, Issue 12, pp.20-25, Nanjing/China.

[16] Zinkevičienė R., Jotautienė E., Juostas A., Comparetti A., Vaiciukevičius E., (2021), Simulation of Granular Organic Fertilizer Application by Centrifugal Spreader. *Agronomy*, Vol.11, Issue 2:247, Basel/ Switzerland.

[17] ***China Academy of Agricultural Mechanization Sciences, (2007), Agricultural Machinery Design Manual (农业机械设计手册). ISBN 9787802333352, *China Agricultural Science and Technology Press*, Beijing/China.

[18] ***Wang G.Q., (2010), Discrete element method and its application in EDEM (离散单元法及其在 EDEM 上的实践), ISBN 9787561227978, *Northwestern Polytechnic University Press*, Xi'an/China.