Research Status on the Helical Conveying Characteristics of Agricultural Materials Based on the Discrete Element Method

Xiaoyuan Zhang*, Yishan Liu, Jingang Zhang, Haoyuan Chen, Ziyu Wen

School of Intelligent Engineering, Jinzhong College of Information, Shanxi, China

*Corresponding author

Abstract

The efficient conveying and processing of agricultural materials are core links in the development of modern agricultural mechanization. As a key technology for studying the dynamics of granular systems at the mesoscopic scale, the Discrete Element Method (DEM) provides an innovative pathway to reveal the mechanisms of agricultural material processing and conveying. This paper systematically reviews the research progress of the discrete element method in the field of agricultural material processing and helical conveying, focusing on the construction of multi-layer structural models, contact parameter calibration methods, process simulation applications, and performance optimization of screw conveyors. The discrete element method can accurately simulate the motion trajectories, force characteristics, and equipment wear patterns of agricultural materials during helical conveying, significantly improving conveying efficiency and optimizing energy consumption. Current research still faces challenges such as multi-physical field coupling modeling and dynamic calibration of complex working condition parameters. In the future, it is necessary to strengthen the deep integration of the discrete element method with machine learning and experimental verification to provide a more solid theoretical foundation for the intelligent design of agricultural equipment.

Keywords

Screw conveyor; Particle; Agricultural materials; Discrete Element Method (DEM).

1. INTRODUCTION

Agriculture, as a fundamental industry of the country, its mechanization and intelligent development represent the core pathway to improve production efficiency and ensure food security. In the full-chain processing of agricultural materials (such as straw, grains, and tuber crops), helical conveying serves as a critical link connecting harvesting, pretreatment, storage, and deep processing, with its performance directly influencing the overall efficiency of agricultural equipment. However, agricultural materials exhibit significant multiphase heterogeneity (e.g., the layered structure of corn straw, the viscoelastic characteristics of granular feed) and operational complexity (dynamic changes in humidity, particle size, and conveying inclination). Traditional design methods based on empirical formulas and macro-scale experiments struggle to reveal the mesoscopic mechanical behaviors between material particles (such as collision, friction, and adhesive fracture) and the interaction mechanism between equipment and materials. This has led to bottleneck issues in conveying systems, such as low efficiency, high breakage rates, and severe wear. How to analyze material movement laws at the microscale and optimize the structure of conveying equipment has become a common technical challenge requiring urgent breakthroughs in the field of agricultural engineering.

Originating from the study of granular systems in geomechanics, the Discrete Element Method (DEM) solves multiscale problems in agricultural material processing by discretizing continuous media into independent particle units and simulating inter-particle contact forces and motion trajectories based on Newton's laws of motion. This technology breaks through the "black box" limitations of traditional experiments, enabling real-time tracking of the dynamic behaviors of tens of thousands to millions of particles, quantitative analysis of key parameters such as force chain distribution, energy dissipation, and wear mechanisms, and achieving a shift from "empirical trial-and-error" to "precision design." In recent years, with advancements in computational power and the development of coupling models, the application of DEM in agricultural engineering has grown exponentially, particularly demonstrating unique advantages in scenarios such as straw shredding and crushing, granular feed conveying, and helical conveying system optimization. For example, by constructing a double-layer adhesive model of straw epidermis and inner pith, it is possible to accurately simulate differences in fracture patterns at different rotational speeds, increasing the shredding palatability rate by 15%; in screw conveyor design, a variable-pitch structure based on DEM simulation can reduce wear by 18%, and a double-screw system can reduce blockage rates of viscous materials by 30%.

Despite the periodic progress made by DEM in the study of agricultural material conveying, its application still faces three core challenges: First, agricultural materials often involve multi-physical field coupling (such as particle plastic deformation in vibration-heat-moisture environments), while existing models mostly focus on single mechanical fields and lack dynamic characterization of complex working conditions; Second, the spatiotemporal variability of material properties (such as moisture content and particle size distribution) leads to insufficient generalization capability in parameter calibration, necessitating the development of intelligent algorithms adaptive to multi-factor coupling; Third, the incomplete cross-scale verification system between simulation results and field tests restricts the engineering applicability of the models. Therefore, systematically combing the research status of DEM in the helical conveying of agricultural materials and analyzing the technological breakthroughs and bottlenecks in key links such as model construction, parameter optimization, and equipment design are of great significance for promoting the transformation of this technology from theoretical research to engineering application.

2. APPLICATION RESEARCH OF DISCRETE ELEMENT METHOD IN AGRICULTURAL MATERIAL PROCESSING

2.1. Construction of Discrete Element Models and Parameter Calibration

Agricultural materials such as corn straw are characterized by a layered structure (e.g., epidermis and inner pith), with significant differences in mechanical properties. Traditional single-layer discrete element models struggle to accurately characterize these differences, leading to large deviations between simulation results and reality. To address this issue, Liu Yuchen et al. [1] established a double-layer bonded bimodal distribution model. By distinguishing the particle properties (e.g., density, elastic modulus, shear modulus) of the epidermis and inner pith, they used the Hertz-Mindlin with bonding contact model in EDEM software to simulate the bonding and fracture behaviors of the two layers. Experiments showed that the elastic modulus of the epidermis (901.36–982.52 MPa) was approximately 30–40 times that of the inner pith (24.48–28.64 MPa), and the shear modulus difference reached 40–50 times, verifying the necessity of the double-layer model. Similarly, Liu Haitao et al. [2] developed a three-dimensional bonded contact model for straw, corn cobs, and grains during the crushing of silage corn grains. They calibrated the critical failure load of each component through compression and shear tests, providing a reference for multi-component material models.

The accuracy of discrete element simulation depends on the precise calibration of inter-particle contact parameters (friction coefficient, recovery coefficient) and bonding parameters (normal stiffness, shear stiffness). Zhang Ruiyu [3] used Plackett-Burman tests to screen key parameters affecting compression displacement (static friction coefficient, recovery coefficient, surface energy, contact plasticity ratio) in a study on the compression of chopped corn straw. A regression model was established through Box-Behnken tests, and an optimal parameter combination (static friction coefficient 0.63, recovery coefficient 0.13, etc.) was obtained. A two-sample t-test between simulations and physical experiments showed no significant differences, verifying the reliability of the parameters. Wang Lei et al. [4] calibrated bonding parameters (critical normal stiffness 2.93×10^{7} Pa, shear stiffness 2.22×10^{6} Pa) for granular feed crushing through texture analyzer tests. They determined the optimal magnitude (10^{10}–10^{11} N/m^{3}) of normal and shear stiffness through quadratic orthogonal rotation combination tests, controlling the simulation crushing force error within 5%.

It is worth noting that parameter calibration must be dynamically adjusted according to material properties. For example, Wang Haoyi [5] found that moisture content and particle size significantly influenced intrinsic parameters such as thermal conductivity and shear modulus in a study on the vibration compression of alfalfa straw, requiring parameter optimization under multi-factor coupling through response surface tests. Additionally, the selection of contact models (e.g., EEPA model, Hertz-Mindlin model) must match material behavior. Niu Zhiyou et al. [6] used the EEPA model for collision crushing of expanded feed, successfully simulating the entire process from local particle crushing to disintegration, with a critical collision velocity simulation error of only 1.6% compared to experiments.

2.2. Discrete Element Simulation and Optimization of Straw Processing Technology

2.2.1 Mechanism of Silk-Rolling and Chopping Processes

The key to corn straw silk-rolling lies in controlling the silk length and size distribution. Liu Yuchen [7] used a double-layer model simulation to find that the chopping speed of the silk-rolling machine affects the fracture patterns of the epidermis and inner pith: at low speeds, the epidermis is mainly torn, while at high speeds, the inner pith breaks more uniformly due to concentrated shear forces. Experiments showed that after optimizing the rotational speed, the silk length distribution range narrowed by 20%, and the palatability rate increased by 15%. Zhang Ruiyu focused on the compression process of chopped straw and found that the inter-particle force chain distribution is closely related to compression density: small particles (≤40 mm) easily fill pores to form tight force chains, while large particles (>80 mm) cause stress concentration, increasing compression energy consumption by 12%. This provides a basis for particle size classification in straw pretreatment.

2.2.2 Compression Molding and Vibration Enhancement

Compression molding is a critical link in straw resource utilization, but traditional compression suffers from uneven stress distribution and high energy consumption. Song Chundong [8] found through vibration compression simulation that when 15Hz vibration is superimposed, stress transmission exhibits a "deep concentration" characteristic, reducing layer-by-layer energy loss compared to traditional compression and decreasing molding pressure by 18%. Wang Haoyi further combined heat transfer analysis to show that vibration promotes frictional heating of particles. At a moisture content of 16%–18%, the thermal conductivity increases by 25%, accelerating material plastic deformation. The optimized combination of vibration frequency (17Hz) and moisture content increased the anti-crushing property of molded blocks by 30% and reduced porosity by 12%.

2.2.3 Design and Verification of Crushing Devices

Grain crushing is a key indicator of silage feed quality. Liu Haitao et al. optimized the roll gap and loading speed of crushing rolls through discrete element simulation and found that when the gap was 2mm and the speed was 4mm/min, the corn grain crushing rate reached 96%, which was consistent with field tests. Sheng Yue [9] addressed the problem of high impurity content in straw harvesting by analyzing the disturbance caused by pulling angles through a root-soil discrete element model. He designed a segmented front curtain and combined rotary blades, reducing stubble height by 6.3% and impurity content by 1.3%, verifying the practicality of discrete element methods in agricultural machinery structure improvement.

2.3. Application of Discrete Element Method in Granular Feed Processing

Extruded granular feed is prone to breakage due to collisions during transportation. Niu Zhiyou et al. divided the crushing states into four categories—intact, partially broken, crushed, and disintegrated—through horizontal collision tests and DEM simulations, determining the critical collision velocity to be 25.2–25.6 m/s (corresponding to an air flow velocity of 56.29 m/s). Simulations showed that when the velocity exceeds the critical value, the breakage rate increases exponentially, and the linear relationship between energy loss and breakage rate transitions to an exponential one, providing a theoretical threshold for air conveying velocity control. Wang Lei et al. found that the shear failure capacity of granular feed (critical shear stiffness: 2.22×10^{6} Pa) is significantly lower than its bearing capacity (normal stiffness: 4.11×10^{10} N/m^{3}), but shear failure is less likely to cause powdering, which differs from the traditional extrusion crushing mechanism. This conclusion provides a basis for the "shear-first" process design in feed processing, such as optimizing the die hole shape of pellet mills to increase shear action and reduce powdering rates.

3. RESEARCH PROGRESS ON THE APPLICATION OF DISCRETE ELEMENT METHOD IN SCREW CONVEYORS

As a bulk material conveying equipment widely used in agricultural and industrial fields, screw conveyors feature simple structures and strong adaptability, playing a key role in scenarios such as feed processing, grain storage and transportation, and biomass processing. However, traditional design relies on empirical parameters, leading to problems such as low conveying efficiency, high energy consumption, and severe wear. The Discrete Element Method (DEM) reveals the movement laws of materials and the wear mechanism of equipment at the microscale by simulating the interaction between particles and mechanical components, providing a new path for the optimized design of screw conveyors.

3.1. Optimization of Conveying Performance and Energy Consumption Analysis

3.1.1 Performance Optimization of Single-Screw Conveyors

The conveying efficiency of horizontal screw conveyors is closely related to rotational speed and filling rate. Xiang Shaoxue et al. [10] found through EDEM simulations that excessively high rotational speeds increase particle centrifugal force, thereby reducing conveying efficiency, with the optimal filling rate being 20%–30%. Yu Ruijiang et al. [11] verified that power consumption is minimized at a rotational speed of 200 r/min and a filling rate of 20%, with a 92% consistency with theoretical calculations. Wu Linghong [12] performed multi-objective optimization on a 35° inclined screw conveyor and obtained optimal parameters (screw diameter 380 mm, rotational speed 100 r/min), controlling the maximum wear depth of the blades within the design limit and extending equipment life by 25%.

In the field of quantitative conveying, Li Yong et al. [13] analyzed mass flow rates at different rotational speeds through discrete element simulations and identified an optimal matching range between filling rate and rotational speed, providing parameter support for precise control in automatic batching systems. Zhang Keping [14] compared conveying performance between constant-pitch and variable-pitch screws, finding that the variable-pitch structure reduces inter-particle extrusion and friction, increasing conveying efficiency by 10% and decreasing breakage rate by 15%.

3.1.2 Synergistic Effects of Double-Screw Conveyors

Double-screw conveyors have become a research hotspot in recent years due to their structural symmetry and complex particle motion. Dai Enliang [15] found through discrete element simulations that co-rotating and counter-rotating dual shafts have no significant effect on mass flow rate, but the coupling effect of pitch and center distance is significant. A regression equation (R^2=0.9646) was fitted between mass flow rate and structural parameters. Xin Yaoyu [16] further noted that each 10% increase in the shaft distance of double-screw conveyors raises mass flow rate by 8%–12%, but excessively large shaft distances cause particle stagnation in the central area. It is recommended to control the ratio of shaft distance to pitch within 1.2–1.5.

Compared with single-screw conveyors, double-screw conveyors exhibit significant advantages in conveying viscous materials. Zhu Hongxiang et al. [17] found that the double-screw structure reduces particle agglomeration, decreases blockage rate by 30% during viscous feed conveying, and consumes 15% less power than single-screw conveyors. These studies provide theoretical support for applying double-screw conveyors in high-viscosity material processing.

3.2. Wear Mechanism and Anti-Wear Optimal Design

3.2.1 Analysis of Wear Influencing Factors

Wear of screw blades is a primary issue restricting equipment life, essentially resulting from high-frequency collisions and friction between particles and blades. Yang Weijie et al. [18] used the Archard wear model to quantitatively analyze the effects of rotational speed and filling rate on wear depth, finding that wear depth increases by 0.03 mm for every 50 r/min increase in rotational speed, while wear amount only increases by 12% when the filling rate increases from 20% to 60%, indicating that rotational speed is the dominant factor in wear. Wu Linghong [19] determined through single-factor analysis and orthogonal tests that screw diameter has the second-most significant impact on wear after rotational speed. The optimized inclined screw conveyor achieved a maximum blade wear depth of 0.1545 mm, below the design limit of 0.225 mm.

Wear area distribution follows a clear pattern: Li Yu et al. [20] found through segmented force analysis that wear on the outer edge of the blade accounts for 65% of total wear, primarily due to high-speed collisions between particles and the blade's outer edge. Wear on the inner side of the blade accounts for only 20% due to lower particle velocities. This provides a clear direction for targeted anti-wear treatments (e.g., hardening coatings on outer edges).

3.2.2 Anti-Wear Structural Optimization

Based on discrete element simulation results, anti-wear design is carried out from two aspects: material selection and structural optimization. In terms of materials, high-hardness alloys or ceramic coatings can improve blade wear resistance, but it is necessary to balance cost and processing difficulty. In terms of structural optimization, Wu Linghong proposed a variable-pitch screw design. By reducing the pitch at the outer edge of the blade, the particle collision speed is reduced by 10%, and the wear amount is decreased by 18%. Xin Yaoyu suggested that double-screw conveyors adopt arc-shaped blade transition zones to reduce particle stagnation and impact at the shoulder, reducing local wear by 25%.

It is worth noting that bionic non-smooth surface design has begun to be applied to screw blades. By imitating the wear-resistant biological surfaces in nature (such as pangolin scales), micro-convex structures are constructed on the blade surface, which can change the particle collision angle and reduce the friction coefficient by 15%–20%. Related studies have entered the simulation verification stage.

3.2.3 Multi-Parameter Coupling and Complex Working Condition Simulation

The inclination angle of inclined screw conveyors directly affects the gravitational component of materials and conveying energy consumption. Wu Linghong found through orthogonal tests that the conveying capacity is optimal at an inclination angle of 30°, and the influence of the filling rate on conveying efficiency significantly increases when the angle exceeds 45°. Shi Yunfei et al. [21] compared dynamic and static feeding methods and found that dynamic feeding can reduce initial energy consumption by 30% and narrow the discharge volume fluctuation range by 20%, revealing the coupling effect between feeding methods and inclination angles.

In silage conveying, Lin Yuan et al. [22] modified the flow calculation formula of screw feeders through response surface methodology, considering the interaction of pitch, rotational speed, and pipe diameter, and controlled the error between simulated flow and actual flow within 4%, providing a reliable model for accurate measurement of wet materials.

Properties such as particle size and moisture content of materials significantly affect conveying behavior. Liu Chunfei [23] compared soybean conveying experiments with simulations and found that the mass flow rate of large particles (>5 mm) is 20% higher than that of small particles, but when the filling rate exceeds 40%, inter-particle extrusion causes a sharp increase in conveying resistance. In the conveying of granular feed, it was found that for every 5% increase in moisture content, the static friction coefficient between particles and blades increases by 8%–10%. It is recommended to reduce the filling rate to below 25% when conveying materials with high moisture content to avoid blockage.

4. RESEARCH PROGRESS ON THE APPLICATION OF DISCRETE ELEMENT METHOD IN AGRICULTURAL MATERIAL CONVEYING

Agricultural material conveying is a critical link in the processing of grain, feed, and biomass resources, with its efficiency and quality directly impacting the level of agricultural mechanization and resource utilization. Agricultural products such as soybeans, Chinese yams, and sunflowers are prone to damage, blockage, or excessive energy consumption due to mechanical effects during conveying. Traditional design relies on empirical parameters, making it difficult to accurately reveal the interaction mechanism between particle motion and equipment. The Discrete Element Method (DEM), by simulating the dynamic behavior of granular systems, analyzes material motion trajectories, force characteristics, and equipment wear patterns at the mesoscopic scale, providing a scientific path for the optimized design of agricultural material conveying equipment.

Conveying oil crops such as soybeans and sunflowers often faces challenges of fragmentation and blockage. Zhao Hongzhen [24] designed a horizontal-vertical screw conveying device and used DEM simulation to reveal the crushing mechanism of soybean grains at the edge of screw blades due to sudden velocity changes. By optimizing the gap to 5 mm and pitch to 85 mm, the breakage rate was reduced from 12% to 5%. Aiming at the blockage problem in the conveying system of sunflower combine harvesters flow deflectors were introduced to optimize the gas-solid two-phase flow field. It was found that a bend diameter ratio of 1.5 increased air velocity uniformity by 25%, improved conveying efficiency from 75% to 94.5%, and reduced energy consumption by 18%.

The accuracy of grain yield metering systems depends on stable control of the conveying process. Lu Changhua [25] established a screw conveying model with an inclination angle of 0°–30° based on EDEM simulation and found a linear relationship (R^2>0.997) between conveying capacity and rotational speed. A supporting metering system was developed, with field tests showing an instantaneous flow error of less than 5.8%, providing technical support for precision agricultural harvesting.

Conveying tuber crops such as Chinese yams requires a balance between soil separation and material protection. Jin Daoxiang [26] designed a vibratory harvester and used DEM to simulate the impact of soil crushing device vibration frequency (8Hz) and amplitude (45mm) on yam damage. It was found that low-frequency and large-amplitude vibrations reduced particle impact energy, with the damage rate decreasing by 30% compared to traditional rigid conveying. Zhou Zhenhui [27] developed a new grain screw stacker using a variable-section vertical screw structure. Simulations showed that the variable-section design increased the average axial velocity of materials by 10%, and conveying efficiency remained stable at a filling rate of 80%, solving the blockage problem under high filling rates.

Efficiency optimization of grain screw conveyors is key to improving the performance of combine harvesters. Yang Yang [28] found through EDEM simulation that excessively high rotational speeds (>1200 r/min) of screw conveyors cause particle stagnation due to centrifugal force. The optimal rotational speed range is 800–1000 r/min, and combined with a filling rate of 40%–50%, it achieves synergistic optimization of conveying efficiency (92%) and power consumption (15% reduction). Zhao Hongzhen further proposed an optimization strategy for the interface position of screw conveyors. Through DEM simulation of particle velocity matching at the junction of horizontal and vertical screws, the breakage rate of soybean grains at the interface was reduced by 40%.

5. CONCLUSION

The Discrete Element Method (DEM) has significantly enhanced the refinement level of agricultural material processing, providing critical parameter support for the design of conveying systems under complex working conditions. As a bridge connecting the micro-scale characteristics of agricultural materials with the macro-performance of equipment, DEM has become a core research tool in the field of agricultural engineering. Its application in the field of screw conveying not only breaks through the limitations of traditional empirical design but also provides a scientific path for the research and development of new high-efficiency, low-energy-consumption, and wear-resistant conveying equipment through the revelation of mechanisms at the mesoscopic scale. With the deepening of computational technology and multidisciplinary integration, DEM is expected to play a more critical supporting role in frontier fields such as smart agriculture and precision operations.

ACKNOWLEDGEMENTS

This paper was supported by "Science and Technology Innovation Program for Higher Education Institutions in Shanxi Province(2022L659)."

REFERENCES

[1] Liu Yuchen. Simulation and Experimental Study on Silk-Rolling of Corn Straw Based on Discrete Element Method [D]. Gansu Agricultural University, 2023.

[2] Liu Haitao, et al. Simulation Analysis and Experiment on Grain Crushing Device for Silage Corn Feed [J]. Journal of Chinese Agricultural Mechanization, 2021, 42(08): 32-39.

[3] Zhang Ruiyu. Research on the Compression Mechanism of Chopped Corn Straw and Optimization of Process Parameters Based on Discrete Element Method [D]. Jilin University, 2023.

[4] Wang Lei. Calibration of Bonding Parameters of Granular Feed and Analysis of Its Crushing Process Based on Discrete Element Method. Feed Industry, 44(01): 10-17.

[5] Wang Haoyi. Study on Heat and Stress Transfer in Vibration Compression Process of Alfalfa Straw Based on Discrete Element Method [D]. Inner Mongolia Agricultural University, 2021.

[6] Niu Zhiyou, et al. Analysis of Collision Crushing Characteristics and Discrete Element Simulation of Expanded Granular Feed. Transactions of the Chinese Society for Agricultural Machinery, 54(08): 371-380.

[7] Liu Yuchen, et al. Mechanical Characteristics Study of Double-Layer Bonded Model of Corn Straw Based on Discrete Element Method [J]. Journal of Northeast Agricultural University, 2022, 53(01): 45-54.

[8] Song Chundong. Study on Stress Transfer Law of Alfalfa Straw Vibration Compression Based on Discrete Element Method [D]. Inner Mongolia Agricultural University, 2020.

[9] Sheng Yue. Improved Design and Experimental Study of Straw Feed Harvester Based on Discrete Element Method [D]. Inner Mongolia Agricultural University, 2021.

[10] Xiang Shaoxue, Wang Xiaole. Analysis of Horizontal Screw Conveying Mechanism Based on EDEM Simulation [J]. Port Handling, 2015, (05): 49-51.

[11] Yu Ruijiang, et al. Simulation and Analysis of Horizontal Screw Conveyor Based on Discrete Element Method [J]. Electronics World, 2015, (21): 168-170.

[12] Wu Linghong. Optimization of Conveying Performance of Screw Conveyor Based on Discrete Elements [J]. Journal of Pingxiang University, 2022, 39(06): 13-17.

[13] Li Yong, Liu Weidong. Discrete Element Simulation and Analysis of Single Screw Based on EDEM Software [J]. Hoisting and Conveying Machinery, 2017, (04): 78-81.

[14] Zhang Keping, et al. Numerical Simulation of Working Process of Screw Conveying Device Based on Discrete Element Method [J]. Agricultural Research in the Arid Areas, 2016, 34(06): 285-291.

[15] Dai Enliang. Performance Research and Optimization of Double-Screw Conveyor Based on Discrete Element Method [D]. Wuhan University, 2018.

[16] Xin Yaoyu, et al. Analysis of Material Conveying and Force Characteristics of Double-Screw Conveyor Based on Discrete Element Method [J]. Journal of Liaoning Shihua University, 2021, 41(04): 63-70.

[17] Zhu Hongxiang, Tan Huan. Performance Research of Screw Conveyor Based on EDEM [J]. Mechanical & Electrical Engineering Technology, 2018, 47(07): 27-29+202.

[18] Yang Weijie, et al. Wear Analysis of Screw Blades Based on Discrete Element Method [J]. Coal Mine Machinery, 2021, 42(07): 69-71.

[19] Wu Linghong. Anti-Wear Optimization of Inclined Screw Conveyor Based on Discrete Element Method [J]. Journal of Taiyuan University (Natural Science Edition), 2023, 41(02): 58-63.

[20] Li Yu, Cui Keyuan. Discrete Element Simulation Study of Horizontal Screw Conveyor Based on Dimensional Analysis Method [J]. Hoisting and Conveying Machinery, 2021, (17): 36-40+46.

[21] Shi Yunfei, et al. Influence of Bunker Feeding Mode on Discharge Volume of Screw Conveyor [J]. Journal of Drainage and Irrigation Machinery Engineering, 2019, 37(04): 341-345.

[22] Lin Yuan, et al. Correction of Flow Calculation of Screw Feeder Based on Discrete Element Method [J]. Food and Machinery, 2020, 36(07): 117-121.

[23] Liu Chunfei. DEM Simulation and Experimental Study on Screw Conveyor Conveying Granular Materials [D]. Beijing Forestry University, 2018.

[24] Zhao Hongzhen. Design and Experiment of Screw Grain Conveying Device for Soybean Combine Harvester [D]. Shenyang Agricultural University, 2024.

[25] Lu Changhua. Development of Grain Yield Metering System Based on Quantitative Screw Conveying Technology [D]. Shandong Agricultural University, 2019.

[26] Jin Daoxiang. Design and Experiment of Vibratory Chinese Yam Harvester Based on EDEM [D]. 2024.

[27] Zhou Zhenhui. Simulation Study on Screw Conveying Characteristics of New Grain Screw Stacker Based on EDEM [D]. Wuhan University of Technology, 2019.

[28] Yang Yang, Cheng Yamin, Wang Zhigang, Tang Feilong. Simulation Study on Conveying Efficiency of Grain Screw Conveyor of Harvester with EDEM. Farm Consultant, 2015, (06): 151-152.