agriculture

Review

Application of Discrete Element Method to Potato Harvesting Machinery: A Review

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Abstract: The Discrete Element Method (DEM) is an innovative numerical computational approach. This method is employed to study and resolve the motion patterns of particles within discrete systems, contact mechanics properties, mechanisms of separation processes, and the relationships between contact forces and energy. Agricultural machinery involves the interactions between machinery and soil, crops, and other systems. Designing agricultural machinery can be equivalent to solving problems in discrete systems. The DEM has been widely applied in research on agricultural machinery design and mechanized harvesting of crops. It has also provided an important theoretical research approach for the design and selection of operating parameters, as well as the structural optimization of potato harvesting machinery. This review first analyzes and summarizes the current global potato industry situation, planting scale, and yield. Subsequently, it analyzes the challenges facing the development of the potato industry. The results show that breeding is the key to improving potato varieties, harvesting is the main stage where potato damage occurs, and reprocessing is the main process associated with potato waste. Second, an overview of the basic principles of DEM, contact models, and mechanical parameters is provided, along with an introduction to the simulation process using the EDEM software. Third, the application of the DEM to mechanized digging, transportation, collection, and separation of potatoes from the soil is reviewed. The accuracy of constructing potato and soil particle models and the rationality of the contact model selection are found to be the main factors affecting the results of discrete element simulations. Finally, the challenges of using the DEM for research on potato harvesting machinery are presented, and a summary and outlook for the future development of the DEM are provided.

Keywords: potato harvesting machine; numerical simulation; DEM; damage avoidance

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1. Introduction

Potato is the fourth largest agricultural crop in the world [1] and one of the most globally consumed staple foods [2]. It is cultivated in over 100 countries and regions [3], playing a significant role in ensuring global food security and economic development [4–6]. According to data released by the *Food and Agriculture Organization of the United Nations* (FAO), global potato-cultivating areas are divided into six major growing environments, as shown in Figure 1 [7], with two each in temperate, subtropical, and tropical environments [8,9]. Global potato production reached 368.8 million tons in 2019, 371.1 million tons in 2020, and 376.1 million tons in 2021. It is expected that annual production will increase with the growth of the global population. Ensuring the efficient and stable development of the potato industry has become a key issue in the agricultural field [10]. The current mechanized harvesting rate of potatoes is low, and potato harvesters face problems such as high mechanical damage rates [11], low operational efficiency, high operational costs, and soil loss in the field during mechanized harvesting [7]. As a result, there is no potato harvester that can currently function in all operational environments, under all soil conditions, and with all potato varieties. Research and development of potato harvesters largely depends on the mechanical operational environment [12]. There are various methods of harvesting potatoes, such as traditional manual methods [13], animal-drawn methods [14], and combine harvesters [15]. Due to the labor-intensive nature of manual potato harvesting and the advancements in agricultural technology, there is an urgent need for transformation from primarily manual methods to mechanized harvesting modes; however, the biomechanical properties of potatoes make it difficult to achieve fully mechanized harvesting throughout the entire process [16]. As one of the main tuber crops and a significant source of starch [17], potatoes are susceptible to mechanical damage during the mechanized harvesting process, which can lead to rot, resulting in significant potato losses each year during the harvesting process [18,19]. Furthermore, sprouting during storage also contributes to potato losses [20]. To ensure sustainable development of the potato industry and global food security, there is a pressing need to develop a potato harvester that can adapt to various operational environments. However, although domestic potato combine harvesters have been developed to a certain extent, gaps exist between them and those developed in foreign countries. There are fewer applications in automatic navigation, intelligent identification, and precise operation. Operational precision and efficiency need to be improved, and their adaptability to complex terrains and different soils is limited. When working in hilly and mountainous areas, there are problems, such as poor passability and difficulty separating potatoes and soil. On the whole, there are shortcomings such as low intelligence level, insufficient adaptability, and insufficient reliability and durability. In contrast, foreign potato combine harvester technology is complex and expensive, increasing farmers' purchasing and operating costs; thus, it is not conducive for use in some economically underdeveloped areas. Additionally, for some special planting patterns or minority varieties of potatoes, the lack of targeted design and optimization means that the technology cannot adequately meet the diverse planting needs.

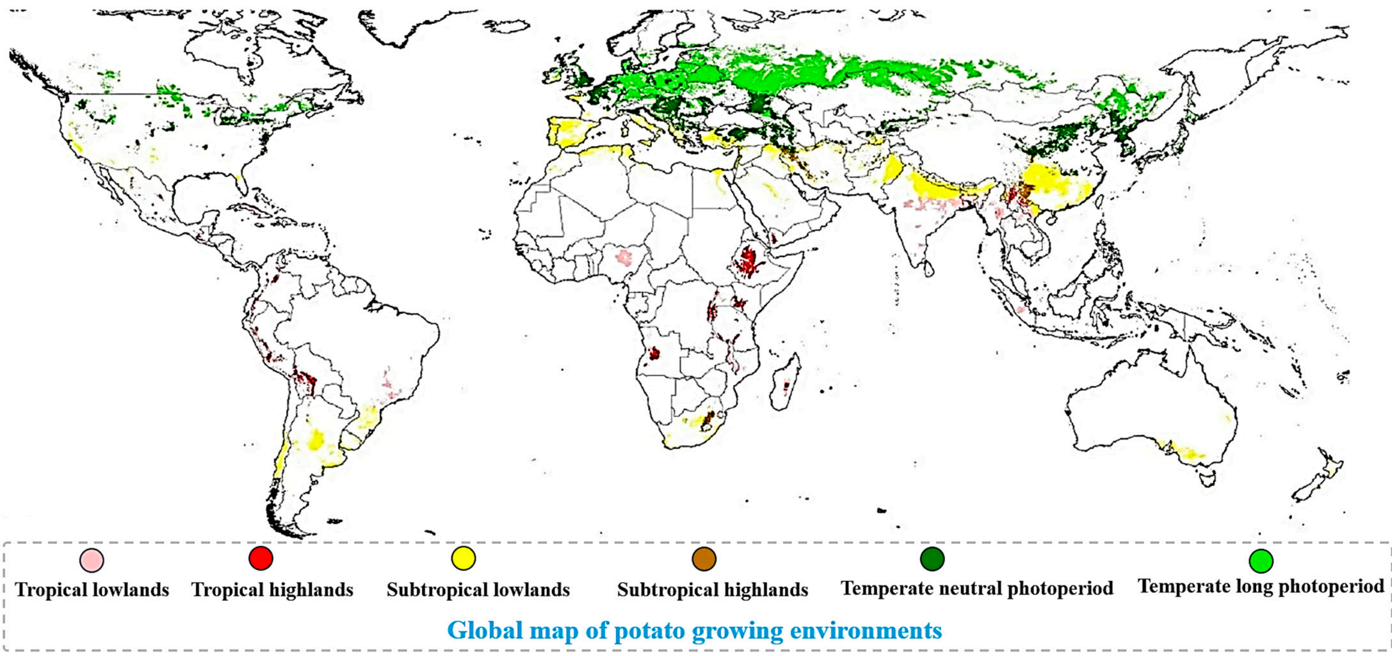


Figure 1. Global map of the distribution of potato growing environments [7].

With the rapid development of computer technologies [21] and new materials science [22], digital design and software simulation have become some of the main methods of engineering design [23–25] and have been widely applied in the field of engineering [26,27]. The application of machine learning and supercomputers has made it possible to simulate large-scale engineering projects [28–30]. The Discrete Element Method (DEM) is one of the primary methods for solving dynamic problems in discrete systems. This method involves numerical calculation and analysis of discrete systems under the premise of considering interactions such as contacts and separations, mutual movements, contact forces between particles, and energy transfers. Therefore, the DEM has been widely applied in agricultural machinery design, operation process simulation, soil flow characteristics, and plant emergence research [31–34].

The data included in this article are sourced from the *Food and Agriculture Organization of the United Nations*, *Web of Science*, etc., and the content and references cited in this article are from sources such as academic conferences, scientific books, and academic journals. The primary academic journals include "*Computers and Electronics in Agriculture*", "*Agriculture*", "*Transactions of the Chinese Society for Agricultural Machinery*", "*Transactions of the Chinese Society of Agricultural Engineering*", etc. Some content is also sourced from academic conference proceedings. The structure of this review is as follows: Part I provides an introduction to potato production and the global scale of the potato industry, as well as the challenges faced during mechanized potato harvesting. Statistical analysis of potato research papers from 2013 to 2014 shows an overall increasing trend, as illustrated in Figure 2a. Using "potato machinery", "agricultural machinery", and "discrete element analysis" as search terms, relevant research literature was statistically analyzed, as shown in Figure 2b. It can be observed that there is a linear correlation between the literature on discrete element analysis of agricultural machinery and research on potato machinery. Part II summarizes the basic principle, contact model, and mechanical parameters of DEM and introduces the simulation process based on the EDEM software. Part III reviews the application of the DEM in the mechanized digging, transportation, collection, and soil–potato separation processes during potato harvesting. Part IV summarizes and outlines the application and shortcomings of DEM in potato harvester research.

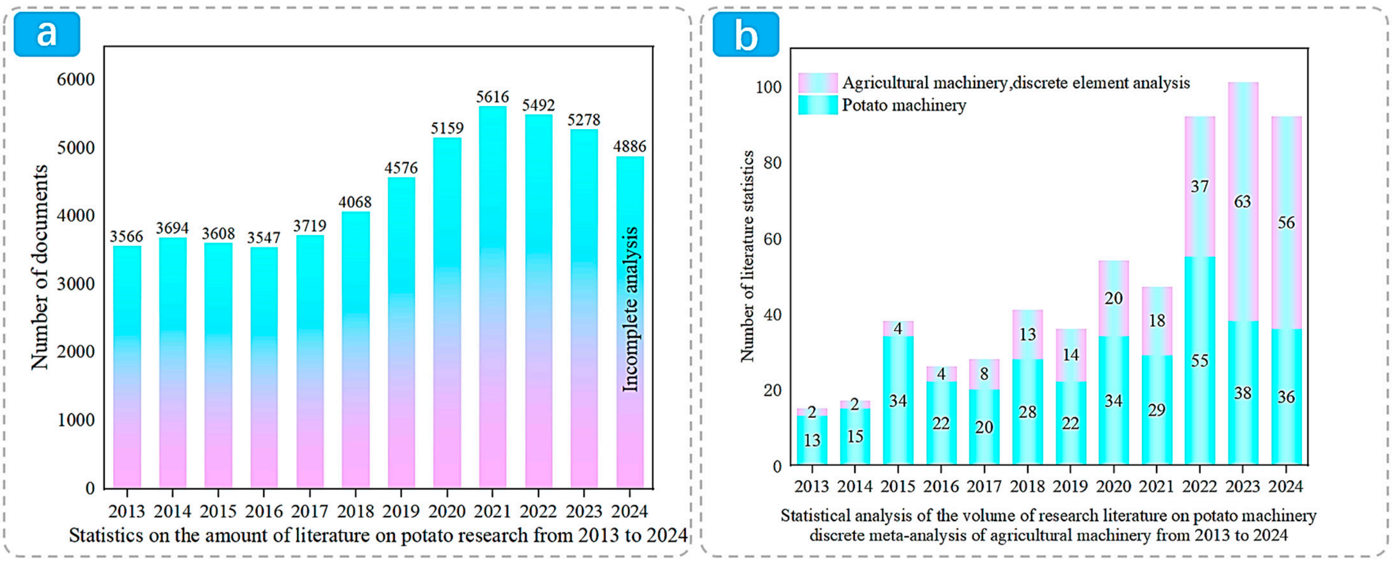


Figure 2. (**a**) Statistical analysis of the research literature on potatoes. (**b**) Statistical analysis of potato machinery, agricultural machinery, and discrete element analysis.

2. Basic Principles of the Discrete Element Method

The DEM is a numerical simulation and calculation method for analyzing and solving the motion laws and mechanical properties of complex discrete systems [35]. The method considers the entire medium as a series of discrete, independently moving particles, with changes in the medium described by the movement characteristics of each unit [36–39]. Initially applied in geotechnical mechanics research, DEM has been used to describe the movement of discontinuous media such as soils and rocks [40,41]. It assumes that there are contacts between particles, and particles in the discrete system can move, rotate, or deform. According to Newton's second law, the acceleration of each particle is obtained, and integration over time is used to calculate the velocity and displacement of the discrete system [42,43]. With the development of computer technology, the DEM has been widely applied in engineering research [44]. From the verification of simple 2D simulation results to complex 3D processes, and from single DEM modeling to the combination of DEM with other technologies, the superiority of DEM in engineering design has been demonstrated [45,46]. Simultaneously, DEM has also been applied in the analysis of soil dynamics. It assesses the importance of contact model particle parameters in soil modeling and obtains parameters for selecting Hertz–Mindlin contact model particles based on various moisture levels [47]. The development of DEM involves the refinement of contact models and particle shape models [48]. The selection of contact models and the determination of parameters directly affect the efficiency and accuracy of DEM simulations [49].

2.1. Contact Model

The contact model describes the contact behavior between particles [50]. In the early days of the DEM, particle interface action was thought to occur through either soft contact or hard contact, leading to important conclusions for the numerical model of discontinuous bodies [51,52]. In DEM, each particle is considered an independent rigid body, and the contact model is used to calculate the forces and torques between these bodies. This section provides a brief introduction to the eight common contact models in the DEM analysis software EDEM.

2.1.1. Hertz–Mindlin No-Slip Contact Model

The Hertz–Mindlin no-slip contact model is a model used to describe the contact behavior between granular materials and is widely applied in DEM simulations. This model combines the normal contact force from the Hertz model and the tangential friction force from the Mindlin model, forming the Hertz–Mindlin no-slip contact model [53,54]. This model can comprehensively describe the contact behavior between particles, including the normal and tangential force–displacement relationships and the frictional effects between particles. It is commonly used to simulate the interactions between particles and geometric shapes. Chen et al. [55] conducted an analysis of the DEM prediction sensitivity for sliding wear of single iron ore particles, which accelerated the calibration of DEM for predicting sliding wear. Li et al. [56] established a mathematical model for the "corn–machine" interaction system based on the Hertz–Mindlin no-slip model. They derived the kinematic and dynamic formulas for the movement of corn ears under the action of the sheller and established a force analysis model for corn–corn interactions, as shown in Figure 3a. Additionally, they analyzed the contact characteristics of "corn–corn" based on the Hertz–Mindlin and bonded models.

In summary, during DEM numerical calculations, the Hertz–Mindlin model requires calibration of parameters using experimental data to ensure the accuracy of the model. For example, parameters such as Young's modulus, Poisson's ratio, and friction coefficient of particles should be measured experimentally to verify the consistency between the model's predicted results and the experimental data.

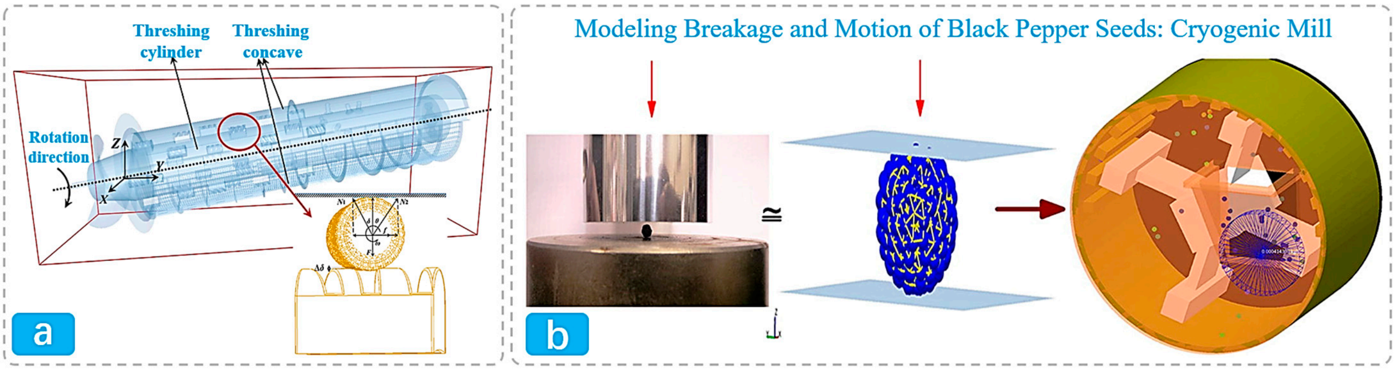


Figure 3. (**a**) Mechanical analysis model of maize [56]. (**b**) Simulation of the process of crushing black pepper seeds [57].

2.1.2. Hertz–Mindlin Bonding Contact Model

The Hertz–Mindlin bonding contact model is specifically designed to simulate the adhesion and fracture behavior between particles in the EDEM software [58,59]. A layer of "binder" is designed between particles to reproduce how small particles adhere and form larger agglomerates. When subjected to external forces, if the adhesive force between these adhered particles exceeds the maximum limit, they will fracture and produce effects of particle breakage in the simulation. Ahmad et al. [60] studied the relationship between soil moisture and cohesive particles using the Hertz–Mindlin bonding model, validating the applicability of the model. Wang et al. [61] integrated the Hertz–Mindlin model with a bonding contact model. The dynamic analysis results were used to replicate actual drilling scenarios while minimizing computational demands. Ghodki et al. [57] coupled the cohesive particle model with the Hertz–Mindlin contact model to analyze the breakage process of black pepper seeds, as shown in Figure 3b. DEM modeling was found to better explain particle breakage and fluidity in grinders.

In summary, the Hertz–Mindlin bonding model allows particles to maintain a bonded state within a certain range of normal and tangential displacements until the maximum shear stress of the bonding force is reached, at which point the bonding breaks and the particles revert to the interaction of hard spheres. This model is particularly suitable for simulating materials that are prone to breakage and fracture under external forces, such as rocks and concrete.

2.1.3. Hertz–Mindlin Thermal Conductivity Model

The Hertz–Mindlin thermal conductivity model is a type of contact model in the EDEM software that considers the thermal conduction effects when simulating the contact behavior between particles [62]. As a variant of the Hertz–Mindlin model, it adds the calculation of thermal conduction on the basis of the Hertz–Mindlin model [63]. The Hertz–Mindlin model is based on the Hertz contact theory and the Mindlin–Deresiewicz tangential force model, allowing for accurate and efficient calculation of normal and tangential forces between particles. Gui et al. [64] analyzed particle mixing and thermal conduction based on the DEM, obtaining particle temperature distribution maps, as shown in Figure 4a. The study demonstrated an effective method for thermal conduction between particles. The Hertz–Mindlin thermal conduction model, on this basis, adds a temperature update mechanism, enabling thermal conduction between particles to be transmitted through contact, which is suitable for occasions requiring temperature analysis. Thermal conduction occurs after particle contact due to temperature differences. This model is particularly suitable for applications where the effect of heat transfer needs to be considered during particle contact [65,66].

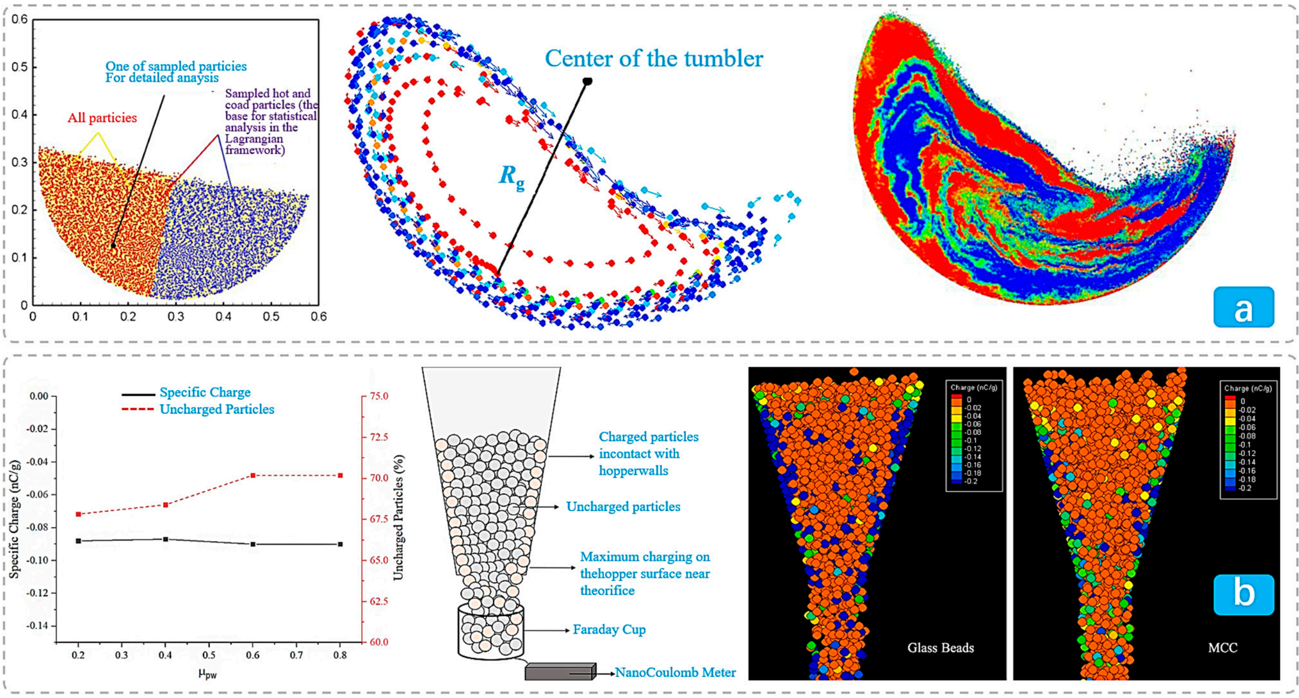


Figure 4. (**a**) Temperature simulation of heat-transferring particles [64]. (**b**) Specific charge analysis of frictionally charged particles [67].

2.1.4. Temperature Update Model

The temperature update model was proposed based on heat flux [68]. It is a physical model in the EDEM software used to simulate temperature changes during particle contact. This model must be used in conjunction with the Heat Conduction model to ensure the correct execution of the thermal conduction algorithm. It is particularly suitable for those application scenarios where heat transfer effects need to be considered during the process of particle contact, such as heat transfer simulation in particle flow in a rotating container.

2.1.5. Linear Cohesion Model

The linear cohesion contact model is a model used in the EDEM software to simulate bonding between particles. This model is suitable for rapid calculations of general cohesive particles and can also be used for moist materials. Unlike the JKR Cohesion model [69,70], which calculates cohesive forces that exist in both the normal and tangential directions of particle contact, the cohesive forces in this model only exist in the normal direction. The linear cohesion model considers the cohesive forces between particles, which are typically caused by intermolecular forces, electrostatic forces, or moisture content. During the simulation, when two particles come into contact and their surfaces are sufficiently close, the cohesive force will bond them together. This model is particularly suitable for applications that require the simulation of bonding behavior between particles, such as the stacking, mixing, or molding processes of powders.

2.1.6. Linear Spring Contact Model

The linear spring contact model is a commonly used contact model in DEM that describes the mechanical behavior of particles during contact. This model is based on the concepts of springs and dampers, where springs simulate the elastic forces between particles and dampers simulate the viscous behavior. The linear spring model typically includes linear elastic frictional behavior and viscous behavior, which act on a very small area, thus transmitting only one force. The linear spring contact model shares similarity with the nonlinear spring contact model. Caserta et al. [71] studied the relationship between the damping coefficient and contact duration in the continuous nonlinear spring–damper contact model within the DEM. Comparing this model to nonlinear contact force models shows that the proposed approximate relationship can effectively reduce the computation time.

In summary, this model is highly useful in the simulation of granular materials, especially when simulating particle interactions without requiring overly complex contact behaviors. For example, it can be used to simulate granular flows, powder stacking, and mixing processes. Due to its simplicity and computational efficiency, the linear spring model is very popular in industrial applications.

2.1.7. Motion Plane Contact Model

The motion plane contact model simulates the linear motion of geometries, with the entire geometry moving at the same velocity [72]. Only when using the moving plane contact model for contact force calculation can a linear velocity be added to the geometry [73]. When setting up the motion plane contact model in EDEM, it is necessary to select appropriate models and parameters based on the specific application scenario and physical characteristics. By adjusting these parameters, more realistic simulation results can be obtained.

2.1.8. Frictional Electrification Contact Model

The frictional electrification contact model is a computational model used to simulate the friction and electrostatic behavior of granular materials during contact [74,75]. This model is typically used to study the physical properties of granular materials, such as powder handling, mixing, and separation in industrial processes. The DEM model considers the contact forces between particles, including elastic forces, frictional forces, and electrostatic forces, as well as how these forces affect the motion and interactions of the particles. Mukherjee et al. [67] predicted frictional charging phenomena during hopper discharge using a simulation model based on the DEM. Specific charge information under different particle–wall frictions was obtained, as shown in Figure 4b. The study concluded that during the simulation of hopper discharge of monodisperse particles, approximately one-third of the particles are expected to remain unchanged, resulting in a relatively large distribution of charge concentrated in a small volume of material. Rasera et al. [76] modeled and analyzed the frictional charging process in both 2D and 3D using the DEM. The method for determining the DEM frictional charging model parameters was found to be effective, resulting in good agreement between the simulation data and experimental data. This approach will improve and simplify the DEM modeling of frictional charging during the handling of dry materials.

2.2. Simulation Process

EDEM is a DEM simulation analysis software widely used for simulating granular materials. The general steps of the EDEM simulation process are as follows: (1) Model building: Establish the model, defining the shape, size distribution, and material properties of the particles (e.g., density, friction coefficient, elastic modulus, etc.). Set the geometric shape and material properties of the container or equipment. Determine the particle generation method, such as through hoppers, airflow, etc. (2) Contact model settings: Choose an appropriate contact model, such as a linear spring–damper model, nonlinear contact model, etc. (3) Interaction characteristics definition: Define the friction, rolling, and torsional characteristics between the particles. If charged particles are involved, it is also necessary to configure the frictional charging model. (4) Simulation initialization: Set the initial conditions, such as the initial positions, velocities, and angles of the particles. Determine the time step and total simulation duration. (5) Boundary conditions and driving forces: Define boundary conditions, such as the interaction of particles with container walls. Add external forces, such as gravity, vibrations, airflow, etc. (6) Running simulation: Start the simulation and perform the calculations based on the specified parameters and models. Monitor the simulation process to ensure stability and that the calculations meet expectations. (7) Analyzing results: Collect and analyze simulation data, such as particle velocities, positions, temperature, pressure distribution, etc. Utilize EDEM's built-in tools or export data to other software for in-depth analysis. (8) Model validation: Compare the simulation results with experimental data or theoretical predictions to validate the accuracy of the model. Adjust model parameters as needed to enhance simulation accuracy. (9) Optimization and iteration: Optimize the process or equipment based on the simulation results. Multiple iterations of the simulation may be needed to find the best design solution. (10) Post-processing and reporting: Create charts, animations, and other visual materials to present the simulation results. The case is shown in Figure 5.

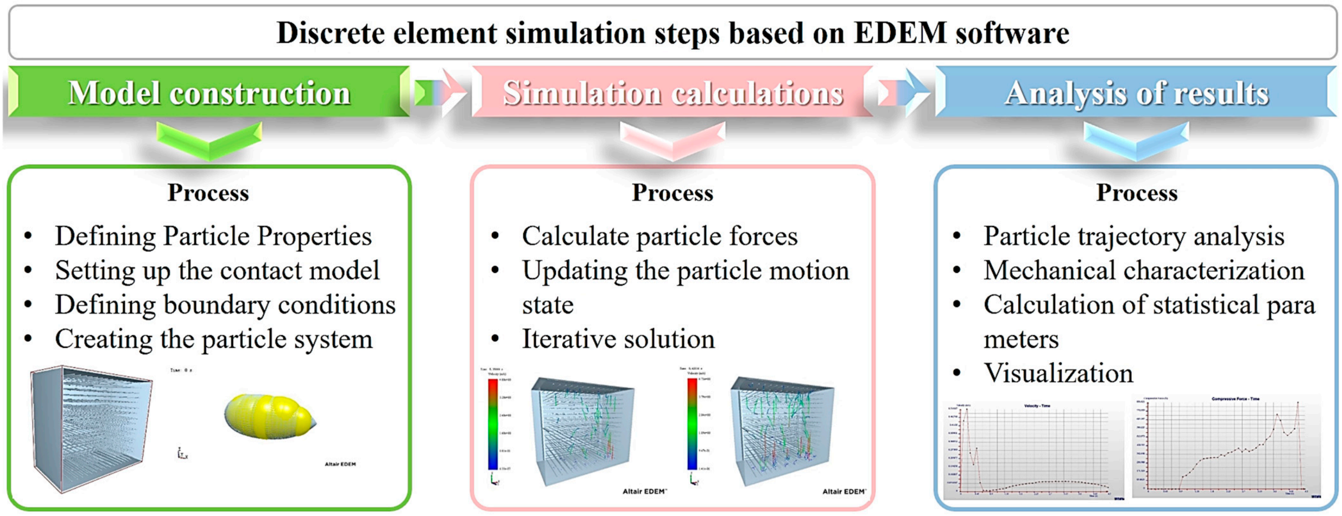


Figure 5. Discrete element simulation steps based on the EDEM software.

The EDEM software provides a user-friendly interface and a comprehensive set of tools to help users efficiently complete the aforementioned process. In addition, EDEM also supports interfaces with other engineering software, such as CAD, CFD, etc., to enable multiscale and Multiphysics-coupled simulations.

2.3. DEM Interaction Design with Potato Harvesters

2.3.1. Key Steps

Inputting mechanical parameters: Key design parameters of potato harvesting machinery, such as the shape, size, and entry angle of the digging shovel, the structure of the separating device, the size of the sieve hole, and the size and rotational speed of the conveying parts, are inputted into the DEM. At the same time, the operational parameters of the harvesting machinery, such as forward speed, digging depth, etc., are set; these serve as the initial conditions of the DEM model simulation and directly affect the accuracy of the simulation results.

Granular material simulation: In the DEM model, potatoes and soil are accurately simulated. Granular materials are endowed with corresponding physical and mechanical properties, including particle density, elastic modulus, Poisson's ratio, internal friction angle, cohesion, etc., in order to reflect the real physical properties of potatoes and soil. The mechanical behavior of potatoes during harvesting was studied by simulating the interaction of granular materials, as well as interactions between particles and harvesting mechanical components, such as collision, friction, extrusion, and so on. Simulation results output and feedback: After running the DEM model for simulation calculation, a series of simulation results data related to the harvesting process are output. These data include the trajectory, speed, and acceleration of potatoes and soil particles; interaction forces between particles and between particles and surfaces of mechanical components, such as friction, crowding force, collision force, etc.; they also include statistical data on damage such as skin abrasion and internal rupture of potatoes during harvesting, and information such as the degree and distribution of soil disturbance during digging and separation. These simulation results are fed back to the operator to provide an important basis for evaluating the performance of the harvesting machinery, identifying potential problems, optimizing machinery design, and adjusting operating parameters.

2.3.2. Key Technologies

Modeling of mechanical parts: Based on the actual structure and size of potato harvesting machinery, the three-dimensional model of each mechanical part is accurately constructed using the CAD software. During the modeling process, the shape and geometric features of the components are defined in detail, as well as the assembly relationship and connection between the components. In this way, the physical structure of the harvester is accurately presented in a digital form, which lays the foundation for the subsequent use of EDEM for simulation analysis.

Granular material modeling: In the DEM model, appropriate granular modeling methods are employed to simulate granular materials such as potatoes and soil. Common granular modeling methods include the spherical particle model, polyhedral particle model, aggregate particle model, etc. Based on the actual situation and research objectives, suitable granular modeling methods are selected, and parameters such as the shape, size distribution, and density of the particles are reasonably set. For example, for soil particles, the proportion of particles in different grain size ranges can be set according to the texture and gradation, and corresponding physical and mechanical properties are assigned to them; for potatoes, they can be simplified into spherical or ellipsoidal particles with certain shapes and dimensions, and their mechanical properties such as elasticity and plasticity are taken into account. Through accurate, granular material modeling, the behavior and interactions of granular materials in the potato harvesting process can be more realistically reflected.

Contact algorithms: In DEM (Discrete Element Method) simulations, accurately calculating the contact forces between particles and between particles and mechanical component surfaces is crucial. To achieve this, efficient and reliable contact algorithms are employed to simulate the contact behavior between particles. Common contact algorithms include the linear spring–damper model, the Hertz–Mindlin contact model, and contact algorithms that couple the discrete element method with the finite element method. These contact algorithms determine the magnitude and direction of contact forces based on different mechanical principles and assumptions by calculating parameters such as relative displacement and velocity between particles. In practical applications, it is essential to select the appropriate contact algorithm based on the characteristics of the particulate material and the requirements of the simulation problem. Additionally, parameters in the algorithm should be calibrated appropriately to ensure the accuracy and reliability of contact force calculations, thereby accurately reflecting the interactions between particles during the potato harvesting process.

Parallel computing: The DEM simulation of the potato harvesting process involves the movement and interaction calculations of a large number of particulate materials, resulting in a substantial computational workload and requiring a long computation time.

Data extraction and analysis: After completion of the DEM simulation, key data relevant to the potato harvesting process are extracted from the simulation results data files. These data include time series information such as the positions, velocities, accelerations, and force conditions of the particles, as well as statistical data on potato damage and soil disturbance levels. Using data analysis methods and tools, the extracted data undergo in-depth analysis and exploration. Statistical analysis methods can be employed to calculate indicators such as the rate of damage to potatoes and the distribution of damage types at different harvesting stages, allowing for assessment of the damage inflicted by the harvesting machinery on the potatoes. Additionally, time-domain and frequency-domain analysis methods can be used to study the variations in the movement speed and acceleration of the particulate materials over time, as well as the frequency components and energy distribution of the interaction forces between particles. This helps to reveal the dynamic characteristics and interaction mechanisms during the potato harvesting process. By extracting and analyzing the simulation results data, detailed information and valuable conclusions about the potato harvesting process can be obtained, providing a scientific basis for performance evaluation, optimization design, and adjustment of operational parameters of harvesting machinery.

Data visualization: Using data visualization technologies, the DEM simulation results are displayed in the form of intuitive and vivid graphics, images, animations, etc., so that researchers and engineers can observe, understand, and analyze the mechanical behavior and the movement of granular materials during potato harvesting. Common data visualization methods and tools include visualization software based on computer graphics (such as OpenGL, VTK, etc.), professional data analysis and visualization platforms (such as MATLAB, Python's related visualization libraries, etc.), and some commercial engineering simulation and visualization software.

Despite the many advantages of using DEM in the simulation of agricultural machinery, there are some limitations to large-scale simulations. Large-scale simulation involves large amounts of particles, with the amount of computation increasing exponentially. This requires high-performance hardware support, and the long time required for computation increases the costs significantly. As the number of particles increases and the model complexity increases, the simulation time increases significantly. This makes the iterative optimization design less efficient and unable to respond to real-world needs in a timely manner.

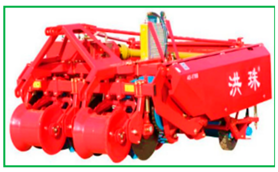
3. Global Analysis of the Current Status of Potato Harvesting Machinery

Mechanized potato harvesting technology integrates the processes of haulm destruction, digging, separation, collection, and loading. Germany, the United States, Italy, Poland, and other developed countries had already achieved integrated mechanized harvesting of potatoes by the 1990s; however, due to limitations in machine size, damage when harvesting fresh potatoes, and high prices, the requirements for mechanized potato harvesting have not been met in China. The potato combine harvester consists of different components—haulm destruction devices, digging devices, conveying devices, soil–potato separation devices, power devices, and control systems—that enable it to harvest mature potatoes. This reduces the cost of potato harvesting and promotes the development of the potato industry.

3.1. Small and Medium-Sized Potato Harvesters

Researchers have developed various types of small and medium-sized potato harvesters designed for hilly and mountainous terrains. These harvesters are characterized by strong maneuverability, low operational costs, and wide applicability. They can address challenges in mechanized potato harvesting on hilly terrains or small plots. This section provides a summary of current typical small and medium-sized potato harvesters, as shown in Table 1. Research on small and medium-sized potato harvesters started relatively late in China, but has developed rapidly in recent years. Enterprises and scientific research institutions have continuously innovated by introducing and absorbing foreign technologies and have developed a variety of products suitable for the nation's conditions. These have performed well when it comes to harvesting small plots in hilly and mountainous clay soil environments; however, overall performance, reliability, intelligence, and other aspects are still lagging behind those of foreign countries. International research on small and medium-sized potato harvesters started early, and the technology has matured. Potatoes in Italy, Poland, Japan, and South Korea are mainly planted in small and scattered mountainous areas, and they are mostly harvested by digging pickup loaders with fixed sorting devices. In countries with large-scale potato planting and relatively flat terrain, combine harvesters are widely used; these countries have made significant progress in intelligence and automation, with stable product performance and high reliability.

Table 1. Structure and technical features of small and medium-sized potato harvesters.

Name	Technical Characteristics	Appearance	Place of Production
WM4000 Potato Harvester	1. This machine is a single-row potato harvester; 2. Overall weight: 4450 kg; 3. Operating speed: 3~5 km/h; 4. Collection box capacity: 4000 kg; 5. Drawbar length: 1250 mm; 6. Its double-row embedded tooth cleaning device enables a more thorough separation of soil and stones [77].		French
1710A Potato Harvester	1. This machine is a trailed potato harvester; 2. Overall weight: 5600 kg; 3. Working efficiency: 8~10 acres/hour; 4. Operating depth: 0~30 cm; 5. Floating disc cutter design reduces digging resistance while cutting weeds [78].		China
4TS-490 Potato Harvester	1. This machine can harvest 4 rows of potatoes in one operation; 2. The reduction in operational resistance reaches over 50%; 3. Structural simplicity; 4. Highly economical [77].		China
4U-90LH Potato Harvester	1. This machine is a trailed potato harvester; 2. Overall weight: 1700 kg; 3. Row spacing: 1050 mm; 4. Working efficiency: 1.5 acres/hour; 5. This model is highly adaptable and can perform well in different soil conditions [79].		China
4U-170B Potato Harvester	1. The machine adopts a double lift chain structure; 2. Overall weight: 1610 kg; 3. Row spacing: 1650 mm; 4. Working efficiency: 7~1.2 hectare/hour		China

	5. The unique lower side of the roller can compact the soil after digging and improve the rate of clearing potatoes, which is convenient for manual picking to improve operational efficiency [80].		
4UFD-1400 Potato Harvester	1. This machine is a trailed potato harvester; 2. Matching power: 44~58.8 kW; 3. Working width: 1400 mm; 4. Operating depth: 0~300 mm 5. It completes the tasks of digging up the potatoes, soil–potato separation, and screening in one go, significantly increasing the rate of harvesting [81].		China
4U-2-900 Potato Harvester	1. This machine is a small traction potato harvester; 2. Operating depth: 20~35 cm: 3. Working efficiency: 2~4 acres/hour; 4. Breakage rate: ≤2; 5. Developed for mechanized potato harvesting in small plots in hilly and mountainous areas. It can complete digging and separating operations in one go [82].		China
TPH179 Potato Harvester	1. This machine is a crawler-type potato harvester; 2. Improves potato harvester maneuverability using tracks as the mode of movement; 3. The whole machine has higher ground clearance [82].		Japan
SHI-1500 Potato Harvester	1. The machine adopts a potato lifting chain conveyor; 2. Separation of potatoes and soil can be accomplished during transportation [83].		Korea
4UL-170C Potato Harvester	1. This machine is a trailed potato harvester; 2. Overall dimensions: 6670 ×2680 × 2890 mm (length × width × height); 3. Overall weight: 3270 kg; 4. Row spacing: 1700 mm; 5. Working efficiency: ≥6 acres/hour; 6. Harvests 2 rows at a time [84].		China

3.2. Large Potato Combine Harvester

International research on large potato harvesters began early, and the technology has reached a mature stage. In regions with significant potato cultivation, such as Europe and North America, the use of combine harvesters is widespread. For example, large combine harvesters in countries like the United States and the Netherlands are equipped with efficient functions for digging, separating, cleaning, and packaging, allowing them to complete harvesting operations in one go. These machines are also highly automated and intelligent, capable of features like autonomous driving, smart recognition, and precise operations, which reduce the need for manual intervention and enhance operational efficiency and quality. Furthermore, advanced technologies, such as those for potato–soil separation, stem and leaf separation, and non-destructive testing, have been adopted to lower the rate of potato damage and improve harvesting quality. In contrast, research on large potato harvesters in China started relatively late but has developed rapidly in recent years. Some companies and research institutions have continuously innovated through the introduction and absorption of foreign technologies, resulting in products like the 1710A combine harvester from Zhongji Meinuo and the 4U-1600 potato combine harvester. While these harvesters meet certain demands of large domestic potato planting bases, there remains a gap in performance, reliability, and intelligence compared to advanced foreign harvesters. Therefore, further efforts in research and development and technological innovation are needed. Statistical analysis of large potato combine harvesters revealed that the majority are from abroad, As shown in Table 2.with several advanced models produced by Grimme, such as the VARITRON series and the VENTOR 4150 series. The potato harvesting machinery produced by the German company GRIMME and the Belgian company AVR can be adapted for the mechanized harvesting of other root vegetables, such as sugar beets and onions, by replacing the front digging and harvesting devices and adjusting the parameters of the separating and conveying devices. This design significantly improves the utilization rate of the equipment. However, domestic potato harvesting machinery still struggles to adapt to the harvesting of potatoes in different soil types.

Table 2. Structure and technical characteristics of large potato harvesters.

Name	Technical Characteristics	Appearance	Place of Production
VARITRON 470 Potato Combine Harvester	1. This machine is a 4-row self-propelled potato harvester; 2. Overall length: 12,810–15,600 mm; 3. Full load weight: 26,000 kg; 4. Collection box capacity: 7000 kg; 5. Discharge height: 4350 mm; 6. Translation: The 7 ton continuous operation hopper utilizes a circulating conveyor belt to ensure that the effective volume is always fully utilized. 7. The harvesting process features multiple automatic functions [77].		Germany
VENTOR 4150 Potato Combine Harvester	1. This machine is a 4-row self-propelled potato harvester; 2. Overall machine length: 15,000 mm; 3. Height: 4000 mm; 4. Full load weight: 30,000 kg; 5. Collection box capacity:15,000 kg; 6. Discharge height:2630–4640 mm 7. Equipped with 530 horsepower and an innovative folding feature [77].		Germany
Double-L 859 Potato Combine Harvester	1. This machine is equipped with a recirculation device, which allows temporarily recirculating harvested potato chunks when changing working tools or loading trucks, thereby improving working efficiency during operations; 2. Overall machine weight: 7260 kg; 3. Power: 200 horsepower [85].		America
AVRSpirit6200 Potato Combine Harvester	1. This machine is a multi-row potato harvester; 2. Collection box capacity: 6000 kg; 3. Power: 90 horsepower 4. Ensure the efficiency and continuity of the machine's operations [77].		Belgium
Dewulf r3060-3 Potato Combine Harvester	1. This machine is a self-propelled potato harvester; 2. It is equipped with a potato vine-killing device at the front, and the soil and potato separating device at the rear can maximize the separation of potatoes from the soil [83].		Belgium
Ropa keiler classic 2 Potato Combine Harvester	1. This machine is a 2-row trailed potato harvester; 2. Bunker: 7.5 t; 3. It has a fully hydraulic drive for optimal adjustment for cleaning;		Germany

	4. It operates independently of the PTO speed and thus maintains all cleaning units in the optimal speed range; 5. It has reduced fuel consumption and tractor engine speed [83].		
Standen T3	1. This machine features a rear-mounted lifting arm trailed structure; 2. Equipped with power above 147 kW and a 12 V DC electrical system; 3. Digging width: 2.5 m; 4. Adaptable ridge spacing: 800–900 mm; 5. Works on 3 ridges simultaneously and can either follow the loading vehicle or lay the potatoes sideways [84].		England

4. Application of DEM in Potato Harvesting Machinery Research

DEM, as a new discrete numerical analysis method, has been widely applied in the field of agricultural engineering [86]. Its main applications include the simulation of soil and mechanical interactions [87], simulation of seed and fertilizer distribution [88], design and optimization of harvesting machinery [89], study of material conveyance and separation [90], research on the wear of agricultural machinery [91], agricultural waste management, and environmental impact assessments [92]. DEM also provides an advanced method for the design, optimization, and performance evaluation of agricultural machinery, contributing to the improvement of efficiency and sustainability in agricultural production [34,93,94]. This section mainly analyzes and summarizes the application of DEM in research on potato harvesting machinery. The application of DEM in the study of potato harvesting machinery includes discrete simulation processes, such as digging, transportation, collection, and separation. By simulating the interaction between the components of the potato harvester and the soil or potato, the structure of the potato harvester can be optimized to improve the harvesting rate, reduce the mechanical damage rate and bruising rate, and provide a solution for the development of mechanized harvesting equipment for tuber crops.

4.1. Simulation and Analysis of the Excavation Process

Currently, potato digging methods are mainly divided into traditional manual and modern mechanical methods [36,95]. Mechanical digging methods use fixed digging shovels, which have high cutting resistance, energy consumption, and severe wear of the digging blade [96]. Another method is biomimetic digging, which involves designing digging shovels based on biomimetic principles; for example, shovels are designed with a contour resembling the claws of a mole cricket, which can reduce horizontal resistance and normal stress, thereby improving the soil fragmentation and soil discharge efficiency [97]. Since the potato digging process involves interactions between potatoes and machinery, as well as the soil system and machinery, research on the mechanization of potato digging will provide an effective way of reducing mechanical damage to potatoes and improving digging efficiency. However, at this stage, the discrete element simulation model for potatoes is a multi-sphere polymer model derived from the Hertz–Mindlin contact model within the discrete element simulation software (EDEM). This model assumes that the potato skin and flesh have the same mechanical properties. This simplistic approach to modeling potato harvesting has hindered the study of potato damage mechanisms during mechanized harvesting by the discrete element method. Gai et al. proposed a new type of potato double-layer flexible bonding model based on the discrete element method. This model accurately simulates the mechanical properties of potatoes and simultaneously mimics the damage characteristics of the skin and flesh. The bonding parameters of the double-layer flexible model for potato samples were refined through shear calibration tests, resulting in the optimal parameter combination. Shear and compression validation tests were conducted on the whole potato stem, and the average relative error between experimental and simulation test results was found to be e = 3.25% [98]. The potato model proposed in this study can more accurately simulate the mechanical properties of potatoes.

Mechanical damage during potato harvesting accounts for 70% of the total damage in the entire potato production system. In order to reduce the rate of mechanical damage to potatoes, Liang et al. [99] used the discrete element method to study the dynamics and kinematics of the soil–potato sorting process. They determined the equivalent Young's modulus of two potato varieties through quasi-static loading experiments. The mechanical parameters of the potatoes were obtained through experimental setups, and a contact force model was developed. The results showed that the newly developed model (R^2 = 0.91 ± 0.06) outperformed the Kuwabara and Kono model (KK model) (R^2 = 0.49 ± 0.09) and the Yigit–Christoforou model (YC model) (R^2 = 0.28 ± 0.13). In this study, the quasi-static and dynamic material properties of two potato varieties were measured using a universal testing system and a self-developed dynamic impact information acquisition test device. The accuracy of different contact models for transient impact processes was checked by calculating Young's modulus and analyzing the impact information of the potato samples. A viscoelastic–plastic contact model designed specifically for potatoes was developed and validated. The analysis revealed significant differences between the measured and fitted values of peak forces for the KK model, indicating a possible overestimation of the dissipation factor during the unloading phase. The less satisfactory fitting performance of the YC model compared to the measured curves may be due to its reliance on purely elastic or purely plastic equations, which may not adequately capture the complex behavior of the potato. On the other hand, the newly developed model fits the measured data very well and is able to better describe the dynamic mechanical behavior of the potato independent of the impact velocity. This study not only provides a feasible experimental method and contact mechanics model for studying the dynamic mechanical properties of potatoes but also lays the foundation for the future development of discrete elemental models for soil–potato sorting systems. Li et al. [96] designed a potato-digging shovel specifically for clay environments based on the bionic principle of pangolin scales. They used the DEM to simulate the resistance encountered by the bionic shovel during the digging process, as shown in Figure 6a. The movement of soil particles on the flat shovel is chaotic, and the number of green arrows is also fewer than on the bionic shovel. Most soil particles have velocities less than 0.788 m/s, while the shovel's speed is 0.84 m/s. However, the velocities of the soil particles moving on the planar shovel are usually less than the velocity of the shovel. This clearly indicates that soil particles are deposited on the shovel, resulting in an overall reduction in velocity and potentially hindering the movement of soil particles. This result explains why the resistance of the flat shovel is greater than that of the bionic shovel. The study demonstrated that the best bionic prototype had a reduction rate of 22.26% during soil box testing and 14.19% during field testing. Ye et al. [100] simulated the distribution and digging trajectory of particles using DEM-MBD coupling. The simulation results found a critical point at a moisture content of 10% in a sandy soil environment, where the shear strength decreased with increasing moisture content. The change pattern in the simulation results was consistent with theoretical calculations, showing that the reduction in digging resistance was proportional to the cohesive strength when particles were fully sheared. The digging curves obtained from the experiment were consistent with the simulation results in terms of key parameter errors. Li et al. [97] designed a longitudinal wave potato digging shovel based on bionic principles and conducted a simulation study using the DEM to compare the digging process of the bionic longitudinal wave shovel with a regular digging shovel, as shown in Figure 6b.

The bionic longitudinal wave potato digging shovel caused greater soil disturbance, leading to better soil flow. The authors also theoretically explained the resistance reduction mechanism of the bionic elements. The bionic longitudinal wave potato digging shovel reduced the resistance by 14.45%, the potato burial rate by 1.34%, and the potato breakage rate by 0.736%. In order to improve the harvesting efficiency of potato harvesters, Li et al. [95] based their work on simulations combined with experimental approaches. They improved the design of the separation and conveying mechanical equipment of potato diggers in heavy soils, focusing on the selection of a mesh-type digging shovel. This digging shovel ensures that minimal soil enters the subsequent separation device while maximizing the protection of the potatoes from damage, thereby reducing the burden on the downstream separation device.

In summary, the discrete element method (DEM) can simulate the interaction between soil and potatoes, allowing for the calculation of friction and compression forces between the two. This helps to clarify the potential for these forces to cause damage to the potato skin and enables tracking of the potatoes' movement trajectories in the soil, providing a basis for optimizing digging equipment. In terms of equipment design, DEM can simulate the working conditions of different shapes and structures of digging components, comparing the forces experienced by various shovel designs during excavation and their impact on potato damage, thus facilitating improvements in component shapes. Additionally, it can simulate the effects of operational parameters such as digging speed and soil penetration depth on excavation outcomes, allowing for the adjustment of optimal parameters to enhance digging efficiency and reduce damage to potatoes, ultimately supporting efficient and high-quality potato harvesting operations.

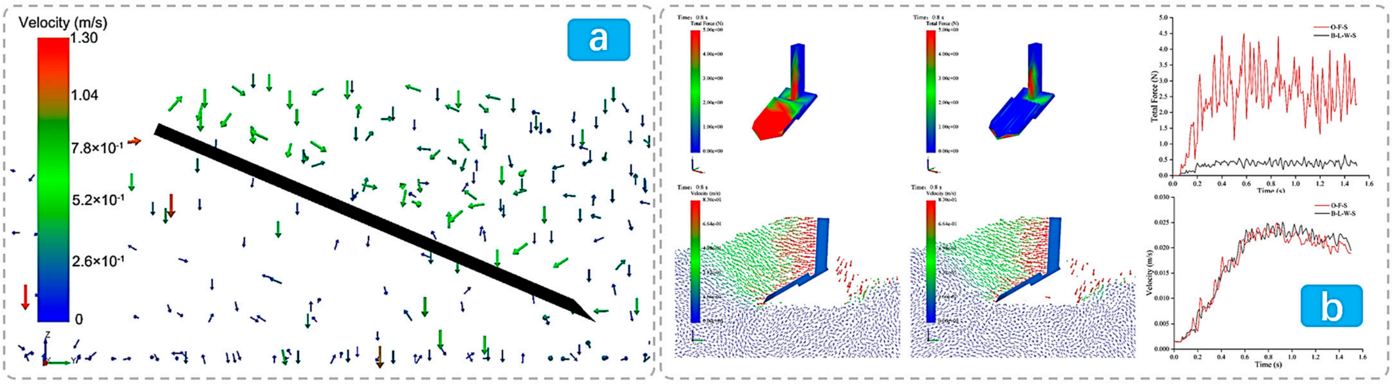


Figure 6. (**a**) Analysis of the digging resistance faced by the bionic shovel [96]. (**b**) Analysis of the digging process of the longitudinal wave potato shovel [97].

In summary, the potato excavation process is a complex mechanical operation that involves interaction between soil and machinery, potatoes and machinery, and potatoes and soil. The DEM can provide an intuitive understanding of the potato-digging process, including the relationship between soil particles and potatoes. According to the simulation results, the mechanical structure of the potato-digging machine can be optimized, thereby increasing the yield of harvested potatoes.

4.2. Simulation of the Potato–Soil Separation Process

Simulation of the potato–soil separation process is a crucial step in the mechanized harvesting of potatoes [101,102]. Its purpose is to separate potato granules from the soil [103]. This process also has the highest probability of causing mechanical damage and bruising the potato granules [104–106]. Several major issues are currently faced during the mechanized harvesting of potatoes: how to thoroughly separate potatoes, soil, and impurities while controlling the mechanical damage rate and bruising rate of potatoes [107,108]. Existing potato harvesters result in unsatisfactory separation of potatoes and soil, high mechanical damage rate and bruise rate, and low potato harvesting rate [109]. Application of the DEM in agricultural engineering has made it possible to simulate the potato–soil separation process. A large number of simulation studies have been reported in recent years. Li et al. [110] investigated the working principle and separation performance of a potato–soil separation device, focusing on the collision characteristics between potatoes and the screen surface and bars. Key factors such as the linear velocity of the separation screen, the forward speed of the harvester, and the inclination angle of the separation screen were considered. Simulation tests were conducted based on the DEM-MBD coupling method. The optimal parameter combination for the potato–soil separation device was determined to be a linear velocity of 1.25 m/s, a forward speed of 0.83 m/s, and an inclination angle of 25°. Field harvesting experiments showed that the potato loss rate was 1.8%, the damage rate was 1.2%, the impurity rate was 1.9%, the skin breakage rate was 2.1%, and the yield was 0.15–0.21 hectares/hour. This research provides valuable theoretical references for simulating potato–soil separation in potato harvesters and optimizing the parameters of these devices.

To solve the problems of poor potato–soil separation and high potato damage rate, Chen et al. [101] designed a rotary vibrating potato separation device and revealed its operating process using DEM-MBD coupling, as shown in Figure 7. The optimal working parameters were determined for the separation process as a vibration point position of 646.5 mm, conveyance speed of the potato–soil separation lifting chain of 1.08 m/s, rotor amplitude of 26.7 mm, and rotor vibration frequency of 5.9 Hz. Field verification experiments were conducted based on these optimal parameters, with potato–soil separation efficiency and potato damage rate of 97.8% and 1.16%, respectively, in the rotor vibration potato separation device. The field test results were consistent with the simulation results, confirming the accuracy of the simulation model. The theoretical DEM provides the references for simulating the rotary vibrating potato–soil separation process and optimizing device parameters. To address the issue of low yield rates of intact potatoes, Du et al. [111] developed a potato–soil separation device combining left and right rotation. They analyzed a DEM model for the potato separation roller, as shown in Figure 8. The force threshold for skin damage to potatoes was demonstrated to be between 190 and 195 N. When the device's incline angle was set at 6°, the separation roller's rotational speed was 100 r/min, the center distance between the separation rollers was 79 mm, the damage rate was 1.25%, the yield rate of intact potatoes was 99.01%, and the skin damage rate was 1.58%. In contrast, with an incline angle of 8°, a separation roller speed was 80 r/min, the center distance was the same at 79 mm, the damage rate increased to 1.43%, the yield rate of intact potatoes dropped to 98.64%, and the skin damage rate was 1.77%. To understand the dynamic relationship between damage and soil separation during potato harvesting using potato harvesters, Li et al. [112] investigated the operating mechanism of the rod-type separator in a small self-propelled potato combine harvester and the performance of a tuber–soil separation. The coupling model was analyzed using DEM-MBD and single-factor simulation experiments. The field tests were validated and revealed an error of 3.81% between the simulation model and field harvesting. However, Yan et al. [113] conducted a simulation study on the process of crushing and separating potato–soil chunks based on the DEM. The study modeled the mechanism of breaking and separating soil clods. Primarily, the three-dimensional model of the separation device was simplified in SolidWorks and imported into the discrete element analysis software (EDEM 2022). The soil breaking and separation simulation is shown in Figure 9a. As the blade rotates above the potato–soil aggregates, the soil is beaten due to collisions. Subsequently, the velocity difference between the blade and the lifting chain drives the potato–soil aggregates to move along the surface of the lifting chain towards the end, continuously breaking and separating the adhered soil particles. Potato–soil breaking and separation were studied in areas with sandy-loam soils.

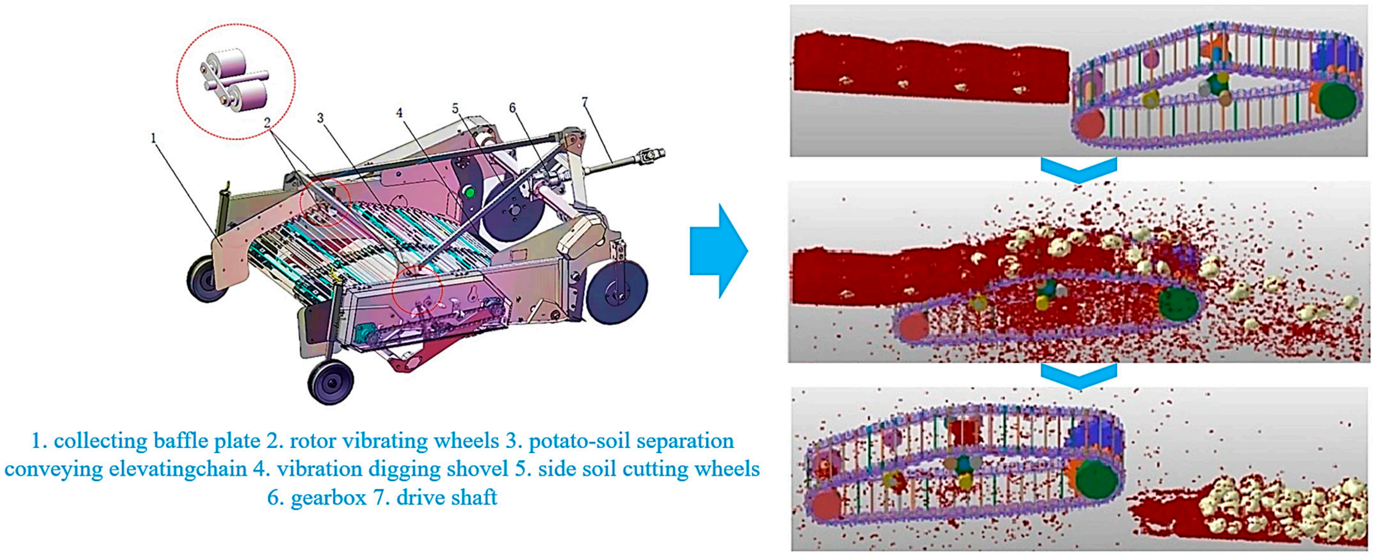


Figure 7. Simulation of the rotor vibration of the potato–soil separation process using a potato separation device. [101]

In summary, the potato–soil separation process is random. Particles in different positions are subjected to slight variations in the soil–potato mixture and the conveying chain; this is correlated with the quality of the soil–potato mixture at different harvest speeds. When the angle of the separation belt increases, fine soil particles can be screened out from the gaps more quickly, improving the soil removal effect. The faster the linear velocity of the separation belt, the quicker the soil is screened; however, this results in shorter soil screening times on the separation device, leading to poor soil cleaning efficiency. The energy required to break the soil clods mainly depends on the shape and characteristics of the clods, such as moisture content. The breakage energy generated by collisions is related not only to the mass of the separation belt and the soil body but also to the initial velocity before the collision. The vibration and breakage of the soil clods are determined by a combination of different linear speeds of the separation belt and the total mass of the soil–potato mixture on the separation mechanism. The increase in the linear velocity of the rod affects its vibration and promotes the breaking of soil clods. To ensure that the potatoes suffer as little damage as possible during the first separation process in the combine harvester, the tubers can be protected by the soil. This is because, after the first potato–soil separation, this portion of the soil will pass through a series of mechanisms of secondary soil removal, including the lifting mechanism. This also ensures the soil removal capability of the combine harvester. The simulation of the potato–soil separation process was reported based on the DEM, which was used to analyze the separation mechanism of potatoes. The mechanical structure was effectively optimized for the potato harvester, and the best operating parameters were determined. This led to an improvement in the efficiency of potato–soil separation, a reduction in the rates of mechanical damage and bruising of potatoes during the separation process, and an increase in the number of marketable potatoes.

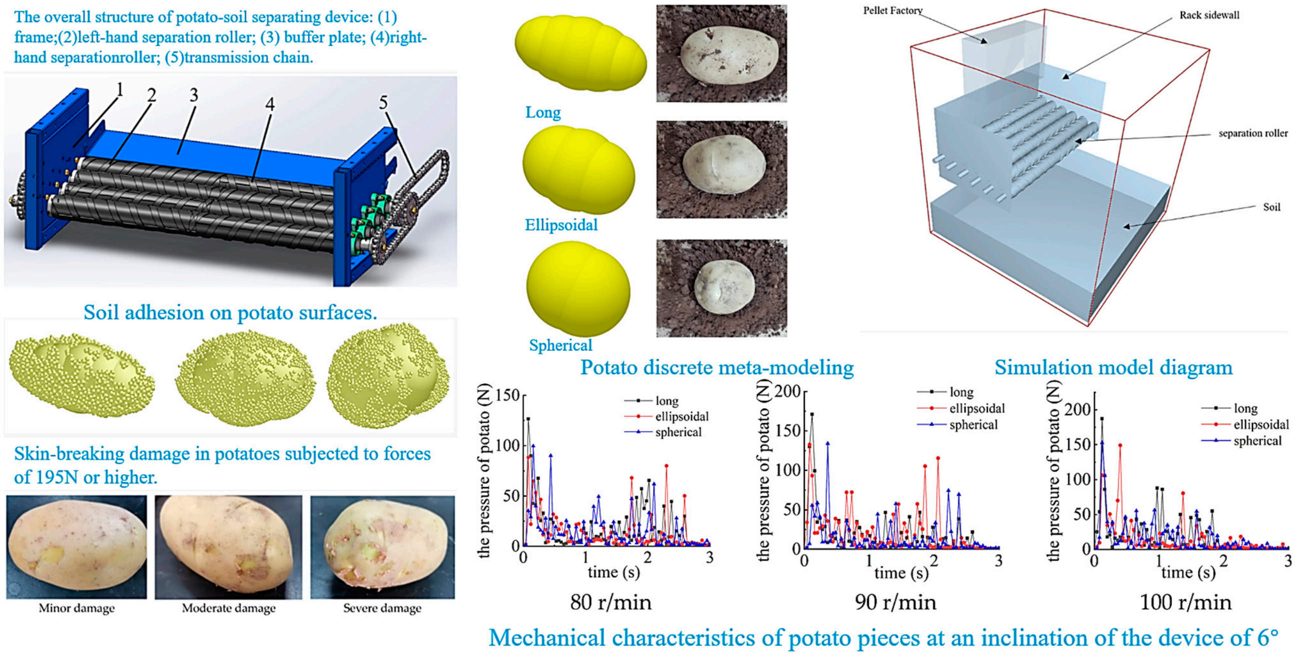


Figure 8. Left–right rotating combined potato separator and discrete element analysis [111].

4.3. Simulation of the Transportation Process

The potato transportation process can be divided into three stages. The first stage involves the conveying of potatoes into the harvester, where the potatoes are transported through the lifting conveyor [114], soil separation device, and other mechanisms to the screening unit. The second stage consists of the screening and conveyance of potatoes to the collection unit. The third stage involves the transportation of potatoes to the storage facility via a transport vehicle [115]. Compared to the digging and soil separation processes, the transportation process inflicts lower mechanical damage and bruising on the potatoes. However, the friction between potatoes results in a higher bruising rate; therefore, the related simulation analysis of this process is an important means of improving transportation efficiency and reducing damage during transportation.

Xie et al. [116] utilized the EDEM software to simulate the potato–soil conveying and separation mechanism and obtained the optimal combination of working parameters. The linear velocity of the conveyor chain was set at 2.3 m/s, with an inclination angle of 18 degrees and an amplitude of 8 mm. Field experiments were conducted to validate the results. The simulation results demonstrated a significant improvement in performance. Lastly, by determining the optimal working parameters and implementing structural innovations, optimization of the potato soil transportation and separation mechanism was achieved. Li et al. [95] used numerical simulation to optimize the potato harvester separation and conveyance machinery. They selected a grille-type digging shovel, which ensures that the amount of soil entering the subsequent separation device is minimized without digging up potatoes and reduces the load on the subsequent separation devices. Zhang et al. [117] conducted research on the soil-lifting device of potatoes based on the TRIZ theory. They used the DEM-MBD coupling model to simulate the operation process of the device, obtaining the optimal operating parameters. Sun et al. [118] simulated the transport process of non-spherical particles in a screw mechanism based on DEM, as shown in Figure 9b. The DEM simulation shows that the particle shape has an impact on the behavior of the flow of the particles and the wear of the conveyor. Subsequently, quantitative assessments of mass flow rate and power consumption were obtained to study the influence of particle sphericity under different operating parameters. The particle collision frequency and collision energy consumption were obtained to investigate possible particle breakage between particles and the screw blade. A comparison of particle–particle collisions and particle–wall collisions showed that particles with larger shape indexes are more likely to be damaged in particle–wall collisions. This research broadens the methods of potato transportation. To reduce the rate of damage to potatoes during the transport process, McRae et al. [119] studied a potato conveyor equipped with an automatic discharge height control device. This control device consists of a sensor ball installed at the end of the conveyor and an air switch that activates an electromagnetic valve to operate a hydraulic lift plunger. The conveyor is divided into two sections, with the distal section capable of swinging laterally when it impacts the rear tailgate of the trailer. Geng et al. [115] studied the influence of initial direction on the trajectory of potatoes under different initial velocities using quadratic coefficients. They found that the influence decreases as the initial velocity increases, and there is a relatively stable state when the initial velocity exceeds 2.0 m/s. Torres-Serra et al. [120] utilized DEM simulations to understand the influence of particle-scale effects on flowability. They investigated the impact of particle size, shape, and hygroscopicity on various bulk-handling issues. The study compared the flow propagation of dry monodisperse spherical particles with particle systems containing size dispersion, prolate spheroid particles, and liquid content in capillary states. This research demonstrates that DEM can be an effective tool for characterizing complex particle flows and improving bulk-handling technologies. Due to the discrete and nonlinear characteristics of materials, the macroscopic characterization of materials depends on the changes in the scale of motion within them. Ren [121] established a discrete element model to study the dynamic characteristics of mesoscale-oriented material flow, obtaining the mechanism of action of various operating parameters on the material movement state. By analyzing mesoscale data, it was found that translation speed and rotation speed are the main factors affecting long-distance movement and material velocity, respectively. Shi et al. [122] also conducted a comprehensive survey and analysis of DEMs in powder transportation systems in the field of powder transportation.

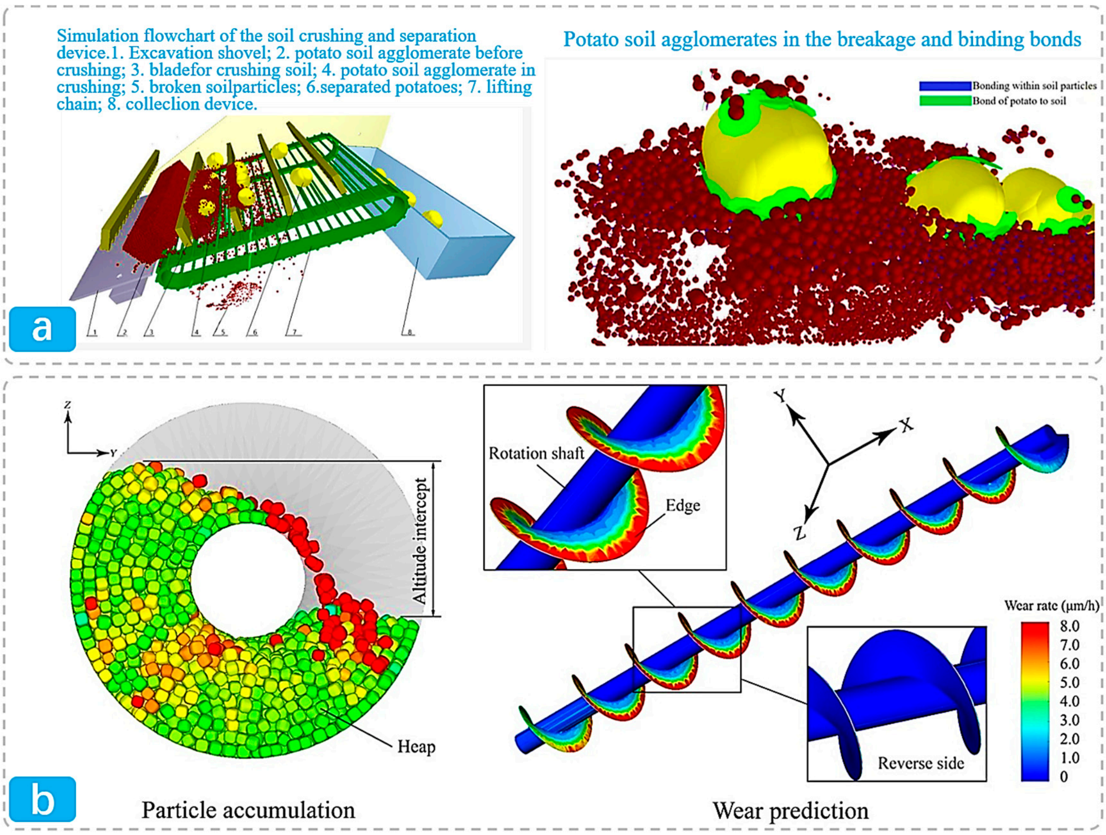


Figure 9. (**a**) Discrete meta-analysis of the potato–soil separation process [113]. (**b**) Discrete meta-analysis of the process of conveying non-spherical particles using the screw conveyor mechanism [118].

4.4. Simulation of the Collection Process

The collection process is usually designed for the convenience of transport vehicles. There are three main technologies. The first one is the potato collection technology, which includes the adaptive height potato collection box technology and the automatic lifting arm conveyor loading potato collection technology. The adaptive height potato collection box technology can automatically adjust the fall height of potatoes, reducing the damage caused by the collision of potato tubers with the box body when they completely enter the separated hopper due to excessive fall height. The second one is the automatic lifting arm conveyor loading potato collection technology. This technology equips the end of the lifting arm with distance sensors such as ultrasonic sensors. Adjusting the hydraulic cylinder changes the tilt angle of the end of the lifting arm and the distance between the lifting arm and the transport vehicle for dropping potatoes. The speed of the lifting arm conveyor can be adjusted according to the quantity of potatoes. This technology has been adopted for potato harvesting models in multiple countries. The third one is human–machine interaction technology, which requires real-time monitoring of the machine's walking status, digging status, conveying and separation status, impurity removal effect, and hopper capacity. This technology integrates mechanical, electrical, hydraulic, and instrumentation technologies and is equipped with a cab terminal human–machine interaction operating system based on PDA/GPS/GPRS/GIS technologies. Dai et al. [123] conducted a simulation study on the solid–liquid two-phase flow during the hydraulic collection process based on DEM-CFD and then confirmed the correctness of the numerical simulation through experiments. Zhang et al. [124] performed a numerical simulation of the sulfurized mineral collection process using DEM-CFD coupling technology. They found that when the roll-up reaches the effective range of the collection hard tube's negative pressure suction, the particles are subjected to the coupling effect of the swirling flow and the negative pressure suction flow and are ultimately transported into the interior of the collection hard tube. Hou et al. [125] established a discrete element model for castor bean three-chamber separation and comminution to analyze the damage to castor beans during mechanical harvesting. The elastic modulus was measured using a TMS pro food physical properties analyzer. The contact parameters were calibrated through the stacking angle. The results showed that the maximum breaking force was 52.65 N. The Box–Behnken response surface design generated the optimal bonding parameters: the normal stiffness per unit area was 9.47×10^7 N/m^3, the shear stiffness per unit area was 4.59×10^7 N/m^3, the normal strength was 7.92×10^3 Pa, and the shear strength was 1.13×10^4 Pa. This study provides support for discrete element simulation parameters to analyze the mechanism of crop damage during mechanized collection processes.

In summary, due to the relatively lower damage to and bruising of potatoes during the collection process, researchers have paid less attention to the study of potato collection and focused more on the digging and soil separation processes during potato harvesting. To reduce secondary damage to potatoes during the collection and transport processes, it is recommended that research be conducted on the movement, collision, and friction between potatoes.

5. Summary and Outlook

With the development of computer software and hardware, the DEM has been widely applied in the field of agricultural engineering, particularly in the design of agricultural machinery. However, agricultural machinery design is a knowledge-intensive process. At present, researchers use numerical simulation technology, with numerical analysis and calculation software such as EDEM, FLUENT, and ANSYS, to conduct finite element analysis and discrete element analysis of the structure and operation of agricultural machinery. This approach reduces the design cost and cycle of agricultural machinery, maximizes the design efficiency, and enriches the design concepts. Although the DEM has demonstrated superior design performance in the design of agricultural machinery, the discrete element method still faces some issues and challenges during the actual design process.

- Limited model accuracy: Although the DEM has certain advantages when it comes to simulating interactions between granular materials and objects, the physical properties of materials such as potatoes and soil are very complex in practical applications, making precise modeling challenging. For example, potatoes have irregular shapes and varying sizes, while the structure and mechanical properties of soil can differ significantly across different regions and conditions. Current models often struggle to fully and accurately represent these real-world scenarios, which may lead to discrepancies between simulation results and actual outcomes.
- Difficulties in parameter calibration: The accuracy of discrete element models largely depends on the precision of model parameters, such as the friction coefficient between particles, elastic modulus, and restitution coefficient. However, accurately determining and calibrating these parameters can be challenging, requiring extensive experimental and empirical data. Moreover, the parameter values may vary under different materials and conditions, which increases the uncertainty and error in the model.
- High computational cost: The computational volume of the discrete element method increases dramatically as the complexity of the simulation increases, for example, considering higher numbers of particles, more complex mechanical structures, and motion processes. The requirements for computer hardware and computation time also increase dramatically, limiting its application in large-scale, complex systems and rapid optimization of the design in practical engineering to a certain extent.
- Insufficient treatment of multi-physical field coupling problems: The potato harvest process not only involves mechanical interactions between particles, but it may also involve multi-physical field coupling problems such as soil moisture migration and heat transfer. At present, the discrete element method has some limitations in dealing with these multi-physical field coupling problems, and it is difficult to fully and accurately simulate various physical phenomena and interactions that occur during the actual harvesting process.
- Lack of systematic research: Currently, the application of the discrete element method (DEM) in potato harvesting machinery research is mostly focused on specific components or processes, such as optimization of the digging shovel or separation screen, and systematic research and comprehensive optimization of the entire harvesting machinery system is lacking. However, potato harvesting machinery is a complex system where various components are interrelated and influence each other. To achieve optimal harvesting results, a holistic and coordinated optimization approach is necessary.

The application of the discrete element method (DEM) in potato harvesting machinery offers significant economic and environmental benefits to the potato industry. By optimizing machine structure and operational parameters through DEM simulations, harvesting operations can become more efficient, reducing work time, labor costs, and fuel consumption. Accurate simulations can help optimize key processes, such as potato–soil separation, minimizing tuber damage and losses, thereby improving harvest quality and increasing farmers' actual income. Utilizing DEM for virtual testing and optimization can reduce the number of actual field trials, shorten the research and development cycle, and lower R&D costs and risks. Precise control of digging depth and force can minimize damage to soil structure and reduce soil erosion and compaction. The improved efficiency of optimized machinery leads to lower energy consumption, which in turn reduces exhaust emissions and other environmental pollutants. In general, DEM has been widely and successfully applied in the field of agricultural engineering, but the research aspect of DEM modeling of soil particles still faces great challenges and has great research prospects, such as modeling soil particles and calibration of particle parameters, simulation of particle loss, and calibration of parameters between soil particles, which still need to be studied in depth.

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