Discrete element modeling and verification of the simulation parameters for chopped hybrid *Broussonetia papyrifera* stems

Caiwang Peng[1*], Junwei Chen[1], Xi He[2], Songlin Sun[1], Yulong Yin[2], Zhong Chen[3]

(1. *College of Mechanical and Electrical Engineering, Hunan Agricultural University, Changsha 410128, China*;
2. *College of Animal Science and Technology, Hunan Agricultural University, Changsha 410128, China*;
3. *Rongcheng Gouyang Modern Agriculture (Chongqing) Co., Ltd, Chongqing 500153, China*)

Abstract: In this study, the discrete element software EDEM was applied to establish a simulation model of non-uniform-sized particle units for *Broussonetia papyrifera* stalks, which aimed to address the low utilization rate of existing *Broussonetia papyrifera* harvesting machinery, the significant variation between the simulated model of *Broussonetia papyrifera* stalks and their actual appearance, as well as the absence of contact parameter calibration. Through a combination of the free-fall collision method, inclined plane sliding method, and inclined plane rolling method, numerical simulation was conducted to analyze the pattern of variations in contact parameters between *Broussonetia papyrifera* stalks and the steel material of the machinery. Accordingly, these parameters were calibrated. The results showed that the coefficient of restitution between *Broussonetia papyrifera* stalks and steel materials was 0.321, the static friction factor was 0.589, and the rolling friction factor was 0.078. With the parameters of contact between *Broussonetia papyrifera* stalks as variables and the experimentally measured pile angle as the objective of optimization, the steepest ascent experiment and the three-factor five-level rotation combination experiment were conducted. In this way, a second-order response model was constructed to analyze the relationship between the contact parameters and the pile angle. Through the optimization analysis of experimental data, it was determined that the coefficient of restitution between *Broussonetia papyrifer*a stalks was 0.21, the static friction factor was 0.24, and the rolling friction factor was 0.03. Furthermore, the calibration results were validated through experimentation to show that the relative error between the obtained pile angle under the context of optimal parameter combination and the actual one was 4.11%. In addition, the relative error of mass flow rate in spiral transport was within a reasonable range, this study lays a foundation both theoretically and statistically for the simulation of contact parameters for *Broussonetia papyrifera* stalk harvesting processing, mechanical harvesting, and so on.

Keywords: hybrid *Broussonetia papyrifera* stem, discrete element method, repose angle, contact parameters, calibration
DOI: 10.25165/j.ijabe.20241701.8408

Citation: Peng C W, Chen J W, He X, Sun S L, Yin Y L, Chen Z. Discrete element modeling and verification of the simulation parameters for chopped hybrid *Broussonetia papyrifera* stems. Int J Agric & Biol Eng, 2024; 17(1): 23–32.

1 Introduction

Hybrid *Broussonetia papyrifera*, also known as paper mulberry, belongs to the Moraceae family. It is characterized by excellent adaptability, strong stress resistance, high biomass, and cutting tolerance[1]. By means of silage, not only is the protein content of Broussonetia papyrifera improved, the fiber and anti-nutritional factors are also reduced, which makes it applicable as an environmental-friendly and efficient ingredient of woody protein feed[2]. Additionally, it is rich in various phytochemicals such as flavonoids, for which it is effective in boosting the immune system of livestock and poultry, suitable as a substitute for antibiotics, and beneficial in maintaining animal health[2,3]. As animal husbandry booms, hybrid *Broussonetia papyrifera* has attracted attention from the livestock sector as an emerging source of non-grain protein feed. At present, the analysis and application research of hybrid *Broussonetia papyrifera* focus mainly on *Broussonetia papyrifera*-made fermented feed[4], *Broussonetia papyrifera* diets[5], *Broussonetia papyrifera* silage[6], and the nutritional value of *Broussonetia papyrifera*. However, the fairly low utilization rate of mechanical harvesting equipment during the harvesting and whole-plant ensiling of *Broussonetia papyrifera* remains. Due to the heavy reliance on manual labor, the level of labor intensity and workload is often very high. Moreover, manual operation has adverse effects on the stubble height of *Broussonetia papyrifera*, subsequent regrowth, and its nutritional composition. This is a severe constraint on the utilization of *Broussonetia papyrifera* and the need for subsequent rotational felling[7].

Moreover, it is necessary to ensure the rational setting of various contact parameters for the simulation model of *Broussonetia papyrifera* stalks, such as static friction factor, rolling friction factor, coefficient of restitution and so on, which lays a foundation for the accurate construction of simulation models and the numerical simulation of cutting and crushing processes as assisted by simulation software. As for those contact parameters, they can be determined through physical experiments. However, due to various influencing factors like experimental conditions, environmental conditions, equipment constraints, and the

Received date: 2023-07-05 **Accepted date:** 2023-10-30
Biographies: **Junwei Chen**, Master candidate, research interest: agricultural engineering, Email: 3559456229@qq.com; **Xi He**, PhD, Professor, research interest: animal husbandry mechanization engineering, Email: hexi@hunau.edu.cn; **Songlin Sun**, PhD, Professor, research interest: design and theory of agricultural equipment, Email: hnndssl@163.com; **Yulong Yin**, PhD, Professor, research interest: animal husbandry mechanization engineering, Email: yinyulong@isa.ac.cn; **Zhong Chen**, General manager, research interest: agricultural engineering, Email: 674337576@qq.com.
***Corresponding author:** **Caiwang Peng**, PhD, Associate Professor, research interest: agricultural mechanization engineering. College of Mechanical and Electrical Engineering, Hunan Agricultural University, Changsha 410128, China. Tel:+86-15173125671, Email: hnndpcw@163.com.

proficiency of operators, it may be difficult to measure certain contact parameters accurately or even impossible to perform measurement. Consequently, there might be a compromise on both the precision of the simulation model for *Broussonetia papyrifera* stalks and the reliability of results obtained from the numerical simulation[8]. With the progress made in computer technology and the diversification of simulation software, the simulation software intended for material simulation model construction, contact parameter calibration, and numerical process simulation have been recognized as one of the major solutions to exploring the parameters of physical properties[9].

The Discrete Element Method (DEM), as a class of discontinuous numerical simulation, has now been widely applied in agricultural productions. DEM is commonly used to conduct model construction, contact parameter calibration, and simulation analysis for various bulky materials such as soil, seeds, and fertilizers[10-12]. Moreover, it is widely applied to the study and model construction of stem materials. For instance, DEM virtual simulation tests and numerical analysis of straw smashing and strip laying were conducted[13]. Wang et al.[14] established a dynamic simulation model to investigate the characteristics of flexible crop stems in terms of dynamic response. Ma et al.[15] calibrated the compression simulation parameters of alfalfa straw through a combination of physical experiments and simulation experiments. Shi et al.[16] constructed a flexible model of sesame stems based on the DEM bonding model and then validated this model for its reliability through stem shear tests and pile angle experiments in combination. Liao et al.[17] performed discrete element simulation tests on the stacking of feed rapeseed stem particles using the Hertz-Mindlin basic model, with simulation parameters obtained for stem fragmentation. Ma et al.[18] built a basic particle sphere model of rice stems based on the Hertz-Mindlin contact model to simulate the process of separating rice from debris during the operation of a combine harvester. Lenaerts et al.[19] proposed a wheat stem model capable of bendable deformation and calibrated the simulated contact parameters. The discrete element parameters of flexible straw and soil are calibrated respectively and a discrete element model for flexible straw mulch soil model was established[20]. And a combined method of the EDEM-recurdyn coupling simulation and the soil tank wear experiment has been implemented to study the interaction and wear between flexible materials and soil. Ma et al.[21] by comparing the results of physical and simulation experiments, the model and calibrated contact parameters were verified for their feasibility and accuracy. From above, it can be found out that both domestic and foreign scholars have conducted extensive research on simulation model construction, contact parameters calibration, and bonding parameter calibration for the stem of different crops. However, there remains little research carried out on the contact between *Broussonetia papyrifera* stems and mechanical equipment. Currently, most stem simulation models consist of multiple continuously stacked basic particle spheres of the same diameter, and numerical simulations are usually conducted using the fixed contact parameters. This way of modeling approach has such advantages as simplicity, fast calculation, and short cycle. Nevertheless, there is still little research conducted on how to calibrate the contact parameters of stem simulation models based on the biological characteristics of *Broussonetia papyrifera* stems. Furthermore, the simulation models of stems often show a significant difference from the actual appearance, thus resulting in the low degree of consistence between simulation results and experimental results.

To address the above-mentioned issues, the hybrid *Broussonetia papyrifera* stalks of the "hybrid *Broussonetia papyrifera* Sci101" is taken as the research subject in this study. After the removal of branches and leaves, the pile angle of the hybrid *Broussonetia papyrifera* stalks was measured through physical experiments. Considering the biological properties of *Broussonetia papyrifera* stalks and the exact requirements for subsequent research, a stem model was constructed using the non-uniform-sized basic particle sphere units that can be used to accurately characterize the superficial and internal structures of the *Broussonetia papyrifera* stalks. Through the *Broussonetia papyrifera* stalk simulation model, numerical simulation experiments were conducted to analyze the pile angle. Besides, the parameters of contact between the particles of *Broussonetia papyrifera* stalks were calibrated. Then, a second-order response model was established to determine the static friction factor, rolling friction factor, and coefficient of restitution. Also, the reliability of the model was verified through experimentation. This study contributes the accurate and reliable simulation model and contact parameters to exploring the mechanical properties of *Broussonetia papyrifera* stalks, the interaction between *Broussonetia papyrifera* stalks and mechanical equipment, and the subsequent simulation research on the cutting and crushing processes during the ensilage of *Broussonetia papyrifera* stalk. On this basis, it is achievable to a high level of consistence between the results of simulation analysis and those obtained from physical experiments.

2 Test materials and methods

2.1 Intrinsic parameter determination of experimental materials

2.1.1 Geometric Dimensions and Distribution Patterns

The experimental material used in this study is the stalks of the hybrid Broussonetia papyrifera, which were cultivated at a test base in Chongqing, as shown in Figure 1. These hybrid trees were grown under the same natural conditions. The optimal height for harvesting ranges between 0.8-1.0 m. At this stage, the entire plant contains a higher level of crude protein but a relatively lower content of lignin and other coarse fibers. Allowing for the need for regrowth after cutting of the Broussonetia papyrifera stalks, the cutting height is recommended to range from 15 to 20 cm. Following a balanced treatment, the cutting height was finalized as (17.5±2.5) cm. Fifty randomly selected individuals of Broussonetia papyrifera were harvested. After the removal of their lateral branches, the diameter of their stems were measured using a digital caliper with an accuracy of 0.01 mm. The stalks exhibit variations in diameter, with thicker bases and thinner tops observed. The average diameter of stems above the cutting height was measured to be 7.13 mm, with the coefficient of variation reaching 2.68%.

Figure 1 Hybrid broussonetia papyrifera stalk

2.1.2 Density and Poisson's ratio

The *Broussonetia papyrifera* stalks were cut and then laid flat in an electric hot air drying oven. With the drying process conducted at a temperature of (103±2)°C for 8 h, the mass was measured and recorded. Subsequently, the samples were subjected to drying in the oven for another 2 h, which is followed by a second-time weighing. The weights obtained from the two measurements were compared, with the samples having a relative error of less than 0.5% considered to be completely dry. By averaging the results of multiple measurements, the moisture content of the Hybrid *Broussonetia papyrifera* stalks was calculated to be 69.12%. An electronic scale with a precision of 0.001 g was used to weigh the *Broussonetia papyrifera* stalk samples several times to obtain the average. Additionally, the volume of the stalk samples was measured using the drainage method, with the average taken from multiple measurements. Through these calculations, the density of the *Broussonetia papyrifera* stalks was determined to be 615 kg/m^3.

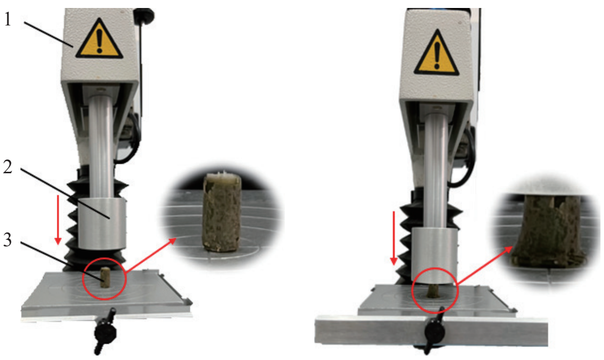
With a length of 100 mm and a diameter of 7 mm, the cylindrical particles of the *Broussonetia papyrifera* stalks were prepared. Single-axis compression tests were performed using the material testing instrument of TA. XTPlus-36/R type, as shown in Figure 2, whose accuracy reaches the centigram level. Also, the speed and length of loading were set at 0.001 m/s and 5 s, respectively. A cylindrical compression probe with a diameter of 0.036 mm was used to repeat the test five times, while the high-speed imaging technology was applied to compare the changes in height and diameter before and after the single-axis compression test. On this basis, the equations used to calculate the elastic modulus, shear modulus, and Poisson's ratio of the *Broussonetia papyrifera* stalks were obtained as follows:

$$E=\frac{\sigma}{\varepsilon_1}=\frac{Fl_0}{S_1\Delta l} \quad (1)$$

$$G=\frac{E}{2(1+\mu)} \quad (2)$$

$$\mu=\left|\frac{\varepsilon_2}{\varepsilon_1}\right|=\frac{\Delta d l_0}{\Delta l d_0} \quad (3)$$

where, E is the elastic modulus of *Broussonetia papyrifera* stalks, MPa; G is the shear modulus of *Broussonetia papyrifera* stalks, MPa; μ is Poisson's ratio; σ is the stress applied to *Broussonetia papyrifera* stalks, MPa; F is the critical compressive force applied during the test, N; S_1 is the cross-sectional area of *Broussonetia papyrifera* stalks before the test, mm^2; l_0 is the length of *Broussonetia papyrifera* stalks before the test, mm; d_0 is the diameter of *Broussonetia papyrifera* stalks before the test, mm; Δl is the change in length of *Broussonetia papyrifera* stalks after the test, mm; Δd is the change in diameter of *Broussonetia papyrifera* stalks after the test, mm; ε_1 is the longitudinal strain; ε_2 is transverse strain.



a. Force mode b. Estroy shape

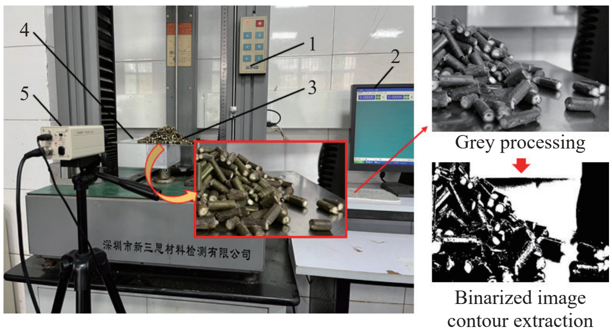
1. Hybrid broussonetia papyrifera stalk particle 2. Compression probe 3. Material testing instrument

Figure 2 Hybrid Broussonetia papyrifera stalk particle compression test

Based on the changes in height and diameter before and after the uniaxial compression test, the elastic modulus, shear modulus, and Poisson's ratio of *Broussonetia papyrifera* stalks were calculated to be 28.59 MPa, 10.43 MPa, and 0.37, respectively. The coefficient of variation was determined as 7.65% for the elastic modulus, 8.21% for the shear modulus, and 5.73% for Poisson's ratio.

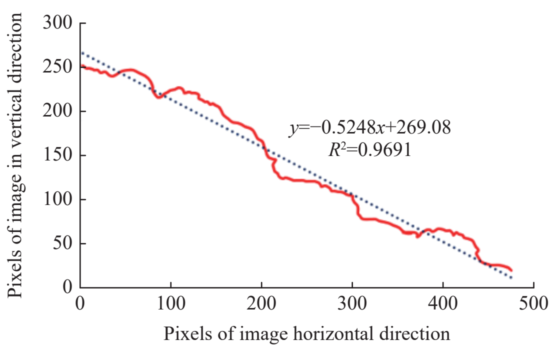
2.2 Physical test on the repose angle of hybrid *Broussonetia papyrifera stems*

Considering the requirements of the silage process and the impact of cutting length on the quality of the entire plant silage, the cutting length is recommended to range from 1.0 to 2.0 cm for the stalks of *Broussonetia papyrifera*[22]. To ensure the accuracy in testing the pile angle of the stalks and improve that of contact parameter calibration, the entire *Broussonetia papyrifera* stalks were cut into three different lengths after the removal of lateral branches: 1.0 cm, 1.5 cm, and 2.0 cm. Then, these segments of the same proportion were mixed uniformly. The pile angle of the stalk particles was measured using the cylindrical lift method on a universal material testing machine (CMT6104). After the formation of a stable particle pile, it was vertically photographed by a camera, as shown in Figure 3a. Matlab was then applied to image processing, which involves grayscale, binarization, and edge fitting. In this way, the slope of the fitted line was obtained, that is, the tangent of the pile angle (Figure 3b). The experiment was repeated five times under the same conditions, and the average pile angle θ of the Broussonetia papyrifera stalks was determined to be 27.24°, with the coefficient of variation reaching 3.13%.



1. Controller 2. Computer 3. Hybrid *Broussonetia papyrifera* stalk heap 4. Steel plate 5. Video camera

a. Cylinder lifting resting angle tester



b. Unilateral contour line and linear fitting diagram of particles

Figure 3 Numerical measurement of repose angle of HBP steam

2.3 Simulation contacts model selection and model construction

In the present study, the stalks of Hybrid *Broussonetia papyrifera* are taken as the research object. Throughout the experiment, these stalks come into contact with other materials, rather than being limited to inter-particle contact, for which forces are exerted. During this experiment, Q235 steel, commonly used to manufacture agricultural machinery, was chosen as the contact material. It has a density of 7850 kg/m³, a Poisson's ratio of 0.30 and a shear modulus of 7.94×10^4 MPa. The simulation experiment was performed using a particle model of the Hybrid *Broussonetia papyrifera* stalks, which is treated as the discrete entities with both geometric and physical properties. The adhesion force is relatively small on their surface. Also, it is assumed that the changes in various parameters during the motion of particles, such as force, velocity, and displacement, are attributed to the insignificant variation in the degree of overlap between particles or between particles and the contact material. According to Newton's second law, the particle model is prone to both motion and rotation under the action of force and torque. According to these assumptions, the motion of the stalk particles was simulated using the Hertz-Mindlin non-sliding contact mechanics model, which is comprised of both normal and tangential force components between the particles, as illustrated in Figure 4. The normal force component is premised on the Hertzian contact force, while the tangential force model is based on Mindlin's research. The tangential friction force follows Coulomb's law, and the rolling friction force is applied through the contact-independent directional constant torque model. For any two contacting spherical particles with particle radii R_i and R_j, the normal overlap δ_n and the normal contact force F_n between particles are calculated using the following equation.

$$F_n = \frac{4}{3}E_1\sqrt{R}\delta_n^{\frac{3}{2}} \tag{4}$$

$$E_1 = \frac{E_iE_j}{E_j(1-u_i^2)+E_i\left(1-u_j^2\right)} \tag{5}$$

$$R = \frac{R_iR_j}{R_i+R_j} \tag{6}$$

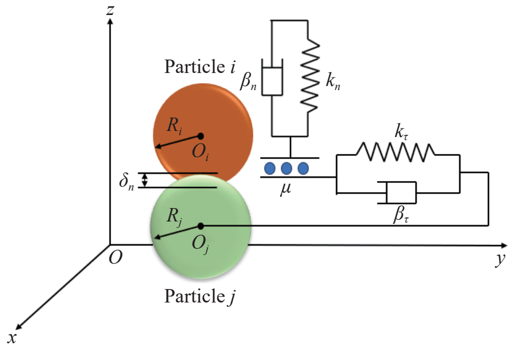
where, E_1 is the equivalent Young's modulus of the stalk particles, Pa; R is the equivalent radius of the stalk particles, m; E_i and E_j are the elastic moduli of the i^{th} and j^{th} particles, Pa; u_i and u_j are Poisson's ratios of the i^{th} and j^{th} particles.

The tangential force F_τ between particles is determined by the tangential overlap and tangential stiffness S_2, and it is expressed as the following equation:

$$F_\tau = -\delta_\tau S_2 \tag{7}$$

$$S_2 = 8G_1\sqrt{R\delta_n} \tag{8}$$

where, G_1 is equivalent shear modulus, Pa.



Note: O_i and O_j are the positions of the sphere centers of two particles, respectively; R_i and R_j are the radii of two particles, respectively, mm; δ_n is the normal overlap amount of particle collisions, mm; k_n and k_τ are the normal and tangential Hooke coefficients of particles, respectively; β_n and β_τ represent the normal and tangential damping coefficients of particles, respectively; μ is the sliding coefficient between particles.

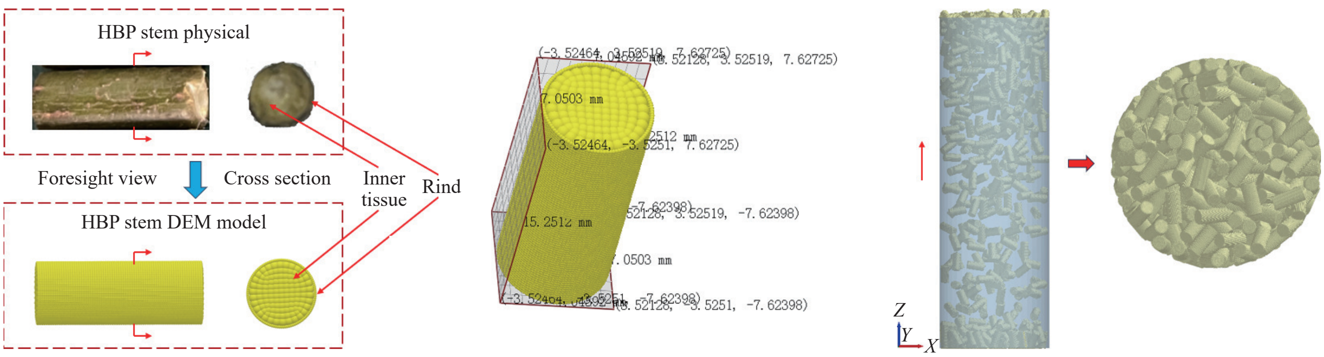
Figure 4 Hertz-Mindlin non-sliding contact model

In discrete element simulation, the rolling friction between particles is usually represented by applying a torque to the contact surface of the particles, as expressed below:

$$T = -u_rF_nR_i\omega_i \tag{9}$$

where, u_r is the rolling friction factor between stalk particles; ω_i is the angular velocity of the particle i at the point of contact, rad/s.

When the basic model of the *Broussonetia papyrifera* stalk particles was constructed for simulating the pile angle, the particle factory API was used to generate the basic particle units, which were then combined at the regular positions and filled with skin and internal tissues (wood and pith). The simulated models of the *Broussonetia papyrifera* stalks have their respective heights of 10, 15, and 20 mm and a diameter of 7 mm. The skin is composed of the regularly-arranged particles with a diameter of 0.3 mm, while the internal tissues are also composed of the regularly-arranged particles but with a diameter of 1 mm, as shown in Figure 5.



a. DEM model of HBP stem

b. Repose angle simulation test

Figure 5 Stem simulation model and repose angle simulation test

The experimental model was simplified at a 1:1 scale in SolidWorks and then imported into EDEM. As shown in Figure 5b, the pile angle simulation experiment of the Broussonetia papyrifera stalk particles was conducted in an environment simulated by using the Hertz-Mindlin (No Slip) contact model. After the simulation experiment was completed, the boundary extraction and fitting method described in Section 2.2 was used to determine the boundaries of the pile angle on both sides of the *Broussonetia papyrifera* stalks.

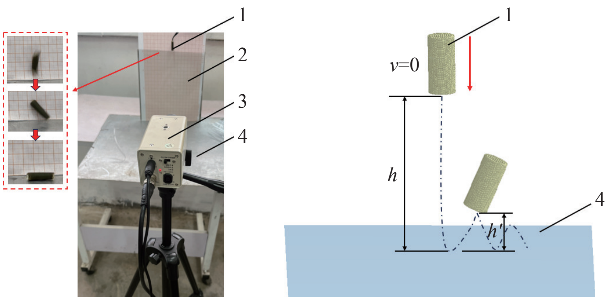
3 Calibration of parameters of contact between *Broussonetia papyrifera* stalk and materials

3.1 Restitution coefficient between stalks and steel material

The restitution coefficient is a parameter that can be used to indicate the capability of an object to recover from deformation during a collision. In general, it is defined as the ratio of the normal relative separation velocity to the normal relative approach velocity of two objects at the point of contact after the collision, which compares to that before the collision[23]. To determine the restitution coefficient, a free-fall test was conducted. In this test, the hybrid *Broussonetia papyrifera* stalks were dropped from a height of 200 mm with an initial velocity v=0 and allowed free fall onto the surface of a steel plate. A camera was used to record the maximum rebound height of the stalk particles, as shown in Figure 6. The equation used to calculate the restitution coefficient e_1 is expressed as follows:

$$e_1 = \frac{|v_2' - v_1'|}{|v_2 - v_1|} = \frac{|v_2'|}{|v_1|} = \sqrt{\frac{h'}{h}} \tag{10}$$

where, v_1 is the initial velocity of the hybrid *Broussonetia papyrifera* stalks before collision, m/s; v_2 is the initial velocity of the steel plate before collision, m/s (since the steel plate is stationary before collision, v_2 is 0); v_1' is the velocity of the hybrid *Broussonetia papyrifera* stalks after collision, m/s; v_2' is the velocity of the steel plate after collision, m/s (since the steel plate remains stationary after collision, v_2' is 0); h is the height of the Hybrid *Broussonetia papyrifera* stalks before collision, mm; h' is rebound height of the Hybrid *Broussonetia papyrifera* stalks after collision, mm.



a. Actual test b. Simulation test

1. *Broussonetia papyrifera* stalk particle 2. Collision bounce test showing grid coordinates 3. Camera 4. Steel plate

Figure 6 Measurement test of particle-steel plate coefficient of restitution

The experiment was repeated 5 times, and the restitution coefficient was calculated using Equation (10). The average of the maximum rebound height of the *Broussonetia papyrifera* stalk particles and the calculated restitution coefficient were calculated to be 20.23 mm and 0.318, respectively.

During the simulation experiment, all contact parameters, except for the restitution coefficient, were set to 0. The restitution coefficient e_1, which represents the interaction between the *Broussonetia papyrifera* stalks and the steel contact material, was treated as the independent variable. Meanwhile, the maximum rebound height h' of the Hybrid *Broussonetia papyrifera* stalk particles was taken as the criterion for evaluation. The restitution coefficients selected for the experiment range from 0.1 to 0.9, with an increment of 0.1. Each set of experiments were conducted 15 times to ensure statistical significance, and the averages were calculated. Subsequently, the experimental results were visualized as a scatter plot and fitted with a curve, as shown in Figure 7.

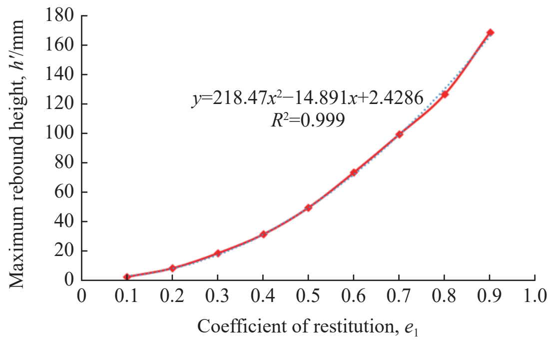


Figure 7 Fitting curves of collision recovery coefficient and rebound maximum height

The fitted equation is expressed as follows:

$$h' = 218.47e_1^2 - 14.891e_1 + 2.4286\ (R^2 = 0.99) \tag{11}$$

By substituting the average rebound height of the *Broussonetia papyrifera* stalk particles and the steel plate material, as obtained from the previous physical experiments, into Equation (11), the restitution coefficient e_1 was calculated to be 0.321. This result was then used for validation through the EDEM simulation. During the simulation, the relative error between the simulated highest rebound height of the *Broussonetia papyrifera* stalk particles and the measurement result was found to be 3.21%. Given these findings, the restitution coefficient between the *Broussonetia papyrifera* stalk particles and the steel plate was finalized as 0.321.

3.2 Static friction factor between stalks and steel material

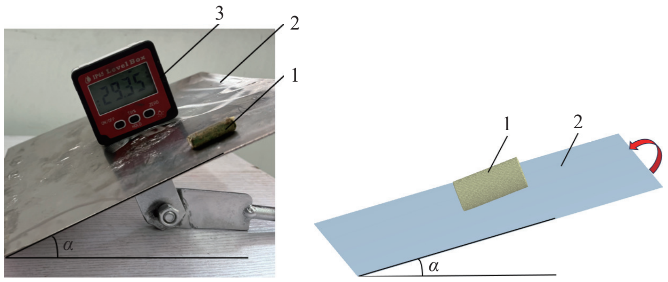
The static friction factor between the *Broussonetia papyrifera* stalks and the steel plate material was calibrated using the inclined plane sliding method, in which a stationary stalk particle with a mass of m on an inclined plane with an angle α is subjected to two forces: F_1 parallel to the inclined plane and F_2 perpendicular to the inclined plane. As the angle α of the inclined plane increases, F_1 increases as well. When the angle α exceeds the critical sliding angle of the object, F_1 reaches a level that is greater than the static friction force f between the object and the inclined plane. As a result, the *Broussonetia papyrifera* stalk particle slides downward. The equation used to calculate the static friction factor is expressed as follows:

$$u_1 = \frac{f}{F_2} = \frac{mg\sin\alpha}{(mg\cos\alpha)} = \tan\alpha \tag{12}$$

In the physical experiment, the stalk particles of *Broussonetia papyrifera* were positioned at the left end of the inclined plane in contact with the steel plate material. The inclined plane was then raised at a low pace until the stalk particles began to slide, as shown in Figure 8. At this time, the angle α between the inclined plane and the horizontal plane was recorded. With the experiment repeated 5 times, the average sliding friction angle between the Hybrid *Broussonetia papyrifera* stalk particles and the steel plate was determined to be 30.15°. Accordingly, the static friction factor was 0.581.

During the course of EDEM simulation, the static friction factor u_1 between the *Broussonetia papyrifera* stalks and the material was considered as a variable, and the inclined plane angle α

was treated as an indicator used for the experiment. With the calibrated restitution coefficient used, all of the remaining parameters of contact between materials were set to 0. The static friction factor was allowed to vary from 0.1 to 0.9, at an increment of 0.1. The simulation was performed at the same rotational speed as in the physical experiment. Immediately after the stalk particles of *Broussonetia papyrifera* started sliding, the angle α of the inclined plane was recorded. The experiment was replicated 15 times, with the average taken. The experimental results were obtained and then visualized as a scatter plot, to which a curve was fitted, as illustrated in Figure 9.



a. Actual test b. Simulation test

1. Inclinometer 2. Steel plate 3. *Broussonetia papyrifera* stalk particle

Figure 8 Measurement of particle-steel plate coefficient of static friction

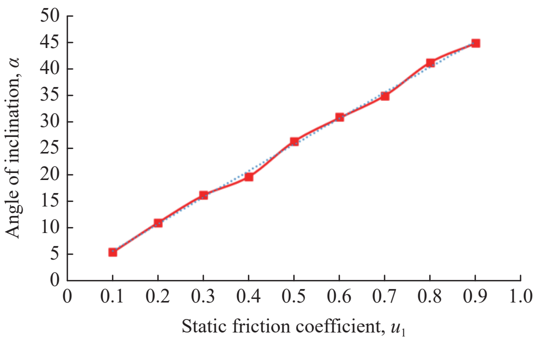


Figure 9 Fitting curves of static friction coefficient and inclination angel

The fitted equation is given as:

$$\alpha = -2.2825u_1^2 + 51.867u_1 + 0.3624\ (R^2 = 0.99) \tag{13}$$

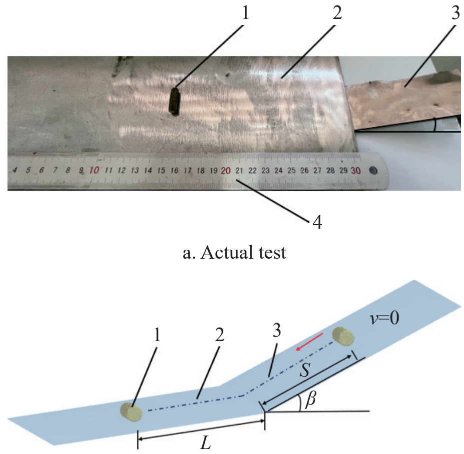
By substituting the angle α measured during the experiment into Equation (13), u_1 was calculated to be 0.589, When this value was used for validation in the EDEM simulation, the simulated sliding friction angle was found basically consistent with the actual one. Therefore, the static friction factor u_1 between the *Broussonetia papyrifera* stalk particles and the steel plate was determined to be 0.589.

3.3 Rolling friction factor between stalk particles and steel material

As shown in Figure 10, the rolling friction factor between *Broussonetia papyrifera* stalk particles and the material was determined using the inclined plane rolling method. When this method was used, stalk particles were released at an initial velocity v=0 on an inclined plane with an angle β. Due to rolling friction, the particles rolled down the inclined plane for a distance S until they stopped on a horizontal plate. Let L be the distance traveled by the stalk particles rolling horizontally. The stalk particles are assumed to be cylindrical in shape, so that the pure rolling process depends only on the rolling friction force, which follows the law of conservation of energy.

$$mgS\sin\beta = mg(S\cos\beta + L)\mu_S \tag{14}$$

where, μ_S represents the rolling friction factor.



b. Simulation test

1. *Broussonetia papyrifera* stalk particle 2. Flat steel plate 3. Inclined steel plate 4. Ruler

Figure 10 Measurement test of particle-steel plate coefficient of rolling friction

During the preliminary experiment, it was observed that the selected stalk particles were not perfect cylinders given an overly small inclination angle β of the inclined steel plate, thus leading to either no rolling or the particles coming to a halt on the inclined plane after rolling a distance S. Conversely, when β was too large, the stalk particles rolled onto the horizontal plate and bounced slightly, which affects the experimental results. To improve the reliability and accuracy of the experimental results, the inclination angle of the steel plate β was set to 20°. To reduce experimental errors, the rolling distance S traveled by the stalk particles on the inclined plane was set to 30 mm. With the experiment repeated 15 times, the average rolling distance as measured on the steel plate was determined as 161.32 mm. Accordingly, the rolling friction factor was 0.094.

To conduct the EDEM simulation experiment, the same method as used in the actual experiment was applied. The collision restitution coefficient and static friction factor were set to the calibrated levels, while the remaining contact parameters were set to 0. Taken as a variable in the simulation, the rolling friction factor μ_S was set to a range of 0.05 to 0.15 at an increment of 0.01. The horizontal rolling distance L was treated as the evaluation index, and the experimental results were visualized as a scatter plot and fitted with a curve, as shown in Figure 11.

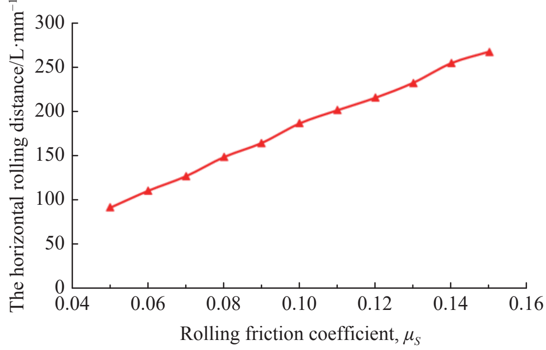


Figure 11 Fitting curves of rolling friction coefficient and inclination angel

The fitted equation is given as:

$$L = 1494.6\mu_S^2 + 2066.5\mu_S - 8.5972\ (R^2 = 0.99) \tag{15}$$

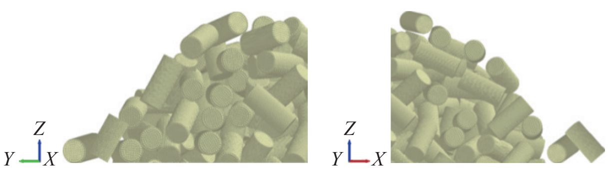
Based on the fitted equation, the rolling friction factor μ_S was calculated using the measured average horizontal rolling distance traveled by the stalk particles on the steel plate. In this case, μ_S = 0.078. Then, the value of μ_S was validated in EDEM, and the relative error between the simulated horizontal rolling distance and the actual rolling distance was obtained, that is, 4.31%. Thus, the rolling friction factor between *Broussonetia papyrifera* stalk particles and the steel plate material was determined to be 0.078.

4 Calibration of parameters of contact between *Broussonetia papyrifera* stalk particles

The parameters of contact between *Broussonetia papyrifera* stalk particles and steel plate materials were calibrated using the aforementioned experimental methods, including the free-fall collision method, the inclined plane sliding method, and the inclined plane rolling method. Additionally, the heap angle was verified by conducting test, where the parameters of contact between *Broussonetia papyrifera* stalk particles were considered as the variables. Also, the relative error between the measured and simulated heap angles was taken as the indicator of evaluation to conduct the steepest ascent experiment. With the measured heap angle as the response value, a three-factor, five-level rotation combination experiment was performed to optimize the results. In this way, the simulated parameters of contact between *Broussonetia papyrifera* stalk particles were obtained.

4.1 Construction and analysis of simulation heap experiment model

The simulation heap angle verification experiment was conducted using the bottomless cylinder lifting method as adopted in the physical experiment. The *Broussonetia papyrifera* stalk particle model as described in Section 2.3 to perform simulation, during which a virtual particle factory was placed above the steel cylindrical material. The particles were dynamically generated, the data were saved at an interval of 0.01 s, and the gravity acceleration was set to 9.81 m/s^2. The size of stalk particles of Broussonetia papyrifera was set to three different levels: 1.0 cm, 1.5 cm, and 2.0 cm, which meets the requirements of ensilage. Immediately after the particles stabilized, the cylinder was lifted at a constant speed of 0.05 m/s, as a result of which the particles fell onto the steel plate because of gravity. The process continued until all the particles stopped moving to form a stable particle heap. By using the angle measurement tool provided by the EDEM software, the heap angle was measured in the +*X* and +*Y* directions of the Broussonetia papyrifera stalk heap, as shown in Figure 12.



a. +*X* projection direction of HBP stalk   b. +*Y* projection direction of HBP stalk

Figure 12 Discrete element model pile for HBP stalk

4.2 Steepest ascent experiment

To determine the optimal factor levels and the range of zero levels for the three-factor, five-level quadratic orthogonal rotation combination design experiment, a steepest ascent experiment was conducted. Based on repeated experiments and literature review[16,17,24], the collision restitution coefficient between *Broussonetia papyrifera* stalk particles was determined to range from 0.15 to 0.65, the static friction factor from 0.20 to 0.70, and the rolling friction factor from 0.01 to 0.11. The factors selected for this experiment include the collision restitution coefficient between *Broussonetia papyrifera* stalk particles (e_2), the static friction factor (u_2), and the rolling friction factor (u_r). The evaluation index is the relative error between the measured heap angle and the simulated heap angle. By using the calibrated parameters of contact between hybrid *Broussonetia papyrifera* stalk particles and steel plates in the EDEM software, the experimental results were obtained, as listed in Table 1.

Table 1 Scheme and results of the steepest ascent experiment

No.	Factors			Test values	
	e_2	u_2	u_r	θ'/(°)	σ/%
1	0.15	0.20	0.01	19.06	30.03
2	0.25	0.30	0.03	26.38	3.16
3	0.35	0.40	0.05	28.37	4.15
4	0.45	0.50	0.07	31.02	13.88
5	0.55	0.60	0.09	40.15	47.39
6	0.65	0.70	0.11	40.56	48.90

According to Table 1, the steepest ascent experiment conducted using the second combination scheme yielded the least significant relative error of 3.16% between the heap angle and the measured heap angle. Therefore, the first, second, and third combination schemes were taken as the codes of three-factor, five-level rotation combination design experiment.

4.3 Quadratic orthogonal rotation combination design experiment

In this experiment, a three-factor, five-level quadratic orthogonal rotation combination scheme was designed to study the collision restitution coefficient (e_2) between Hybrid Broussonetia papyrifera stalk particles, the static friction factor (u_2), and the rolling friction factor (u_r). The simulated heap angle *Y*/θ' was treated as the evaluation index. Regression analysis was performed using the Design-Expert software to determine the optimal combination of parameters through the response surface method. The details on factor coding are listed in Table 2, while the experimental design and results are listed in Table 3. The coded values for factors e_2, u_2, u_r are denoted as *A*, *B*, and *C*, respectively.

Table 2 Experiment factors and codes

Level	Factors		
	e_2	u_2	u_r
–1.682	0.15	0.20	0.01
–1	0.19	0.24	0.02
0	0.25	0.30	0.03
1	0.31	0.36	0.04
1.682	0.35	0.40	0.05

According to the regression variance analysis of the test result listed in Table 4, the *p* values of the single factor items *B* and *C* and the interaction items *AB*, B^2 and C^2 were all <0.01, which were extremely significant influencing factors of the response value *y*. The *p* values of the single factor item *A* and the interaction item *AC*, *BC*, A^2 were more than 0.05, it was an insignificant influencing factor of *y*. The results of the influence of relevant experimental factors on the response value show that there is a quadratic relationship rather than a simple linear relationship.

Table 3 Experiment scheme and results

No.	Factors			$y(\theta')/(°)$
	A	*B*	*C*	
1	0.19	0.24	0.02	26.98
2	0.31	0.24	0.02	22.93
3	0.19	0.36	0.02	25.34
4	0.31	0.36	0.02	28.53
5	0.19	0.24	0.04	27.55
6	0.31	0.24	0.04	24.68
7	0.19	0.36	0.04	28.38
8	0.31	0.36	0.04	30.14
9	0.15	0.30	0.03	28.67
10	0.35	0.30	0.03	27.88
11	0.25	0.20	0.03	23.23
12	0.25	0.40	0.03	28.14
13	0.25	0.30	0.01	22.6
14	0.25	0.30	0.05	27.96
15	0.25	0.30	0.03	27.84
16	0.25	0.30	0.03	28.21
17	0.25	0.30	0.03	27.23
18	0.25	0.30	0.03	28.36
19	0.25	0.30	0.03	27.64
20	0.25	0.30	0.03	27.59

Table 4 Analysis of variance for the relative error in stacking angle

Sources	Sum of squares	df	Mean square	*F*-value	*p*-value
Model	78.97	9	8.77	20.30	<0.0001
A	0.80	1	0.80	1.84	0.2044
B	25.08	1	25.08	58.02	<0.0001
C	18.71	1	18.71	43.28	<0.0001
AB	17.61	1	17.61	40.74	<0.0001
AC	7.813E-003	1	7.813E-003	0.018	0.8957
BC	0.68	1	0.68	1.57	0.2388
A^2	1.03	1	1.03	2.37	0.1546
B^2	6.07	1	6.07	14.04	0.0038
C^2	9.04	1	9.04	20.92	0.0010
Residual	4.32	10	0.43		
Lack of fit	3.45	5	0.69	3.93	0.0797
Pure error	0.88	5	0.18		
Cor total	83.30	19			

R^2=0.948; R^2_{adj}=0.901; CV=2.44%; R_{Pred}=0.654

In addition, according to the regression variance analysis result, the *p*-value of the model coefficient was <0.0001, which was extremely significant, while the *p*-value of the lack of fit term was 0.0797 greater than 0.05, which was extremely insignificant, and the coefficient of variation CV=2.44%, which is low. This showed that the second-order response model between the stem-stem contact parameters and the repose angle obtained from the regression variance analysis was reliable, and the predicted value of the model had a high degree of fitting with the physical test value. The determination coefficient R^2 and corrected determination coefficient R^2_{adj} of the second-order response model were 0.948 and 0.901 respectively. The predicted determination coefficient R_{Pred}=0.654. This showed that the regression model was extremely significant and the influencing factors *A*, *B*, and *C* had a high degree of interpretation for the response value *y*, and that the second-order response model could better predict and optimize the repose angle of chopped cotton stems under different conditions. According to the regression variance analysis result and code factors, the second-order response model between the stem-stem contact parameters and the repose angle had been obtained, as shown in Equation (16):

$$y = 27.80 - 0.24A + 1.36B + 1.17C + 1.48AB - 0.031AC + 0.29BC + 0.27A^2 - 0.65B^2 - 0.79C^2 \quad (16)$$

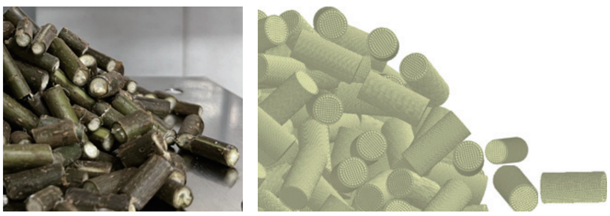
With several sets of optimal parameters obtained, the relevant parameters were finalized as follows. The collision restitution coefficient is 0.21, the static friction factor is 0.24, and the rolling friction factor is 0.03. A set of simulation heap angle experiments were conducted using these optimal parameters to obtain the results showing a high degree of consistence with the actual test results, whether in terms of angle or heap shape. The average heap angle obtained from multiple test runs is 28.36°, which means a relative error of only 4.11% when compared to the actual heap angle. It demonstrates the accuracy and reliability of the obtained optimal parameters. Thus, they are suitable for use in the subsequent EDEM simulation experiments.

4.4 Numerical fitting and test verification

In order to verify the accuracy and reliability of the constructed second-order response model between the Hybrid *Broussonetia papyrifera* stalk contact parameters and the repose angle, the repose angle of the chopped Hybrid *Broussonetia papyrifera* stem obtained by physical tests was used as the target value. The target value was fitted by the Optimization module in the Design-Expert software, the regression equation was solved as well as the response surface was analyzed, objective and conditional constraint equations are,

$$\begin{cases} \theta'(A,B,C) = 27.24° \\ \text{s.t.} \begin{cases} 0.15 \le A \le 0.35 \\ 0.20 \le B \le 0.40 \\ 0.01 \le C \le 0.05 \end{cases} \end{cases} \quad (17)$$

According to Equation (17), the contact parameters such as the coefficient of restitution, static friction coefficient, and rolling friction coefficient corresponding to repose angle were obtained. The relevant parameters were finalized as follows. The collision restitution coefficient is 0.21, the static friction factor is 0.24, and the rolling friction factor is 0.03. A set of simulation heap angle experiments were conducted using these optimal parameters to obtain the results showing a high degree of consistence with the actual test results, whether in terms of angle or heap shape, as shown in Figure 13. The average heap angle obtained from multiple test runs is 28.36°, which means a relative error of only 4.11% when compared to the actual heap angle. It demonstrates the accuracy and reliability of the obtained optimal parameters. Thus, they are suitable for use in the subsequent EDEM simulation experiments.



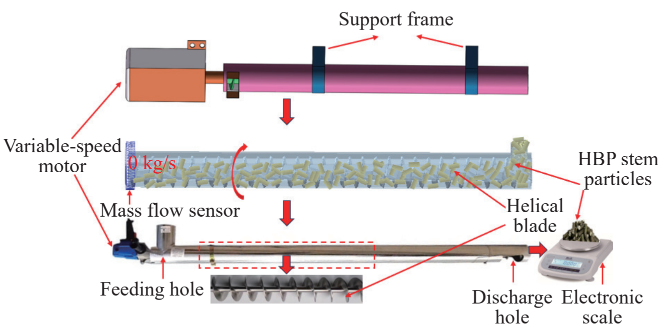
a. Physical test b. Simulation test

Figure 13 Repose angle physical test and simulation test

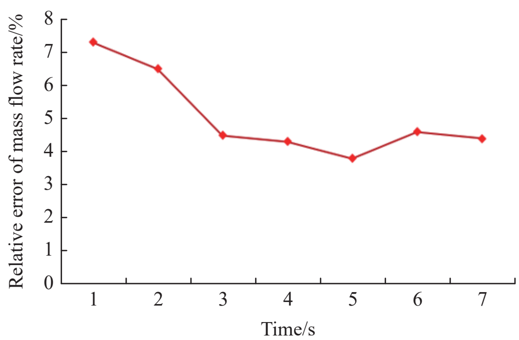
In the process of resource utilization of HBP, mechanization of HBP silage is the successful guarantee of HBP silage process. In order to reduce working procedures, improve working efficiency and facilitate transportation, screw conveying extrusion and integrated equipment are designed and adopted in the process of HBP harvesting conveying, crushing, mixing, extrusion, bagging and binding. It has the advantages of small vibration, good continuity and simple structure, which is conducive to the integration of the whole machine, realizing continuous and stable material conveying and subsequent additive silage and compaction process. On the basis of physical test and EDEM simulation and parameters calibration, screw conveying device is used to further verify the reliability and accuracy of the calibration parameter, as listed in Table 5. By analyzing spiral conveying process and outlet flow, the expected test results can be achieved. The spiral conveyor platform includes support bearing, variable frequency speed regulating motor, feeding port, inner tube insert, spiral conveying chamber, and electronic scale, stopwatch etc. In order to reduce computer simulation load and improve calculation efficiency, the outer diameter, inner diameter, pitch of spiral blade are set as 80 mm, 32 mm, 80 mm, and the thickness, length of spiral delivery pipe are set as 3.5 mm, 1000 mm, respectively, as shown in Figure 14. As can be seen from the test results in Figure 14b, When the end material flow is relatively stable, the relative error of the mass flow rate of materials output was gradually stable at around 4.5% in the end. At first, the simulated mass flow rate of the HBP stem in the spiral inner cavity was higher than that in the actual test, because there was some friction between the HBP stem and the inner cavity of the pipeline. The phenomenon of local extrusion accumulation was caused, and the relative error of the test became large. When the stem was filled with a certain proportion along the spiral cavity, the spiral blade push and extrusion action was relatively stable, and the experimental comparison results show that the material flow was relatively stable, and the relative error was reduced and kept within a certain range, which further verifies the accuracy of the simulation parameters of the HBP stem, and can provide basic data for further research on the HBP silage process.

Table 5 Simulation parameters

Parameters	Value
Poisson's ratio of HBP stalk	0.37
Poisson's ratio of steel	0.30
Shear modulus of HBP stalk G_1/Pa	10.43×10^6
Shear modulus of steel G_2/Pa	7.94×10^{10}
Density of HBP stalk ρ_1/(kg·m^{-3})	615
Density of steel ρ_2/(kg·m^{-3})	7850
HBP stalk-HBP stalk restitution coefficient	0.21
HBP stalk-HBP stalk static friction coefficient	0.24
HBP stalk-HBP stalk rolling friction coefficient	0.03
HBP stalk-steel restitution coefficient	0.321
HBP stalk-steel static friction coefficient	0.589
HBP stalk-steel rolling friction coefficient	0.078



a. Screw conveying device structure



b. Curve of mass flow test relative error

Figure 14 Analysis of spiral conveying experiment and results

5 Conclusions

In the present study, hybrid *Broussonetia papyrifera*, or "hybrid *Broussonetia papyrifera* Stems Sci101" to be exact, was studied. To begin with, the density of the stalk particles was determined using the drainage method, while the heap angle of cut stalks was measured through physical experiments. Then, a discrete element simulation model of the *Broussonetia papyrifera* stalks was established using simulation software. Besides, heap angle simulation experiments were performed. Through regression analysis, a second-order response model for the contact parameters and heap angle of the stalks was constructed. Additionally, the parameters of contact between the stalk particles were experimentally calibrated and validated to ensure the reliability of the model. This study contributed the accurate and dependable simulation model and contact parameters to the simulation research on the mechanical properties possessed by the stalks of *Broussonetia papyrifera* and their interaction with the mechanical equipment. The conclusions drawn from this study are as follows:

A simulation model of stalks of the *Broussonetia papyrifera* was developed using the discrete element simulation software. The model relies on the non-uniform-sized basic particle spheres, which are strategically combined at the regular locations, to represent the outer skin and inner structure of the stalk (wood and pith). The height of the model variation was set to 10 mm, 15 mm, and 20 mm, respectively, while the diameter was set to 7 mm. The outer skin was filled with the particles of a 0.3 mm diameter, while the inner structure was filled with the particles of a 1 mm diameter.

To calibrate the contact parameters, experiments were conducted in the test rig using the EDEM software. The collision restitution coefficient, the static friction factor, and the rolling friction factor were determined to be 0.321, 0.589, and 0.078 through free-fall experiment, inclined plane sliding experiment, and inclined plane rolling experiment, respectively.

Heap experiments were performed to measure the physical heap angle of the stalk particles. The experimental data were processed by using the Design-Expert 8.0.6 software and a response surface optimization method based on quadratic regression orthogonal rotation combination experiments. Thus, the optimal parameter combination for the physical heap angle was finalized. Specifically, the collision restitution coefficient was 0.21, the static friction factor was 0.24, and the rolling friction factor was 0.03. A set of simulation experiments were performed to verify this optimal combination as capable to produce a relative small error of 4.11% between the heap angle obtained from the test and the actual physical heap angle, moreover, the relative error of mass flow rate in spiral transport is within a reasonable range, which confirms the reliability of the simulation model parameters determined in this study.

The simulation model established in this study can only be used for the calibration of contact model parameters, but not for the numerical simulation of the destruction process. On the basis of this model, a cotton stem simulation model representing failure characteristics will be constructed by particle replacement method, and the bonding characteristic parameters will be calibrated.

Acknowledgements

The authors acknowledge that this work was financially supported by the Natural Science Foundation of Hunan Province, China (Grant No.2023JJ30310) and Scientific Research Fund of Hunan Provincial Education Department (Grant No. 22A0169). The authors thank the anonymous reviewers and the editor for their careful reading and many constructive comments and suggestions on improving the manuscript.

[References]

[1] Peng X J, Liu H, Chen P L. A chromosome-scale genome assembly of paper mulberry (*Broussonetia papyrifera*) provides new insights into its forage and papermaking usage. Molecular Plant, 2019; 12(5): 661–677.

[2] Tian H, Chen Y, Zhu N, Guo Y Q, Deng M, Liu G B, et al. Effect of *Broussonetia papyrifera* silage on the serum indicators, hindgut parameters and fecal bacterial community of Holstein heifers. AMB Express, 2020; 10: 197.

[3] Zhang X J, Gao Z L, Wang P S, Xiang L Y. Nutritional value of *Broussonetia papyrifera* fermentation and silage and its application in animal production. Acta Ecologiae Animalis Domastici, 2021; 42(7): 78–81. (in Chinese)

[4] Zhang X, Zhu S Z, Yang Q, Su Z X, Tan H. Effects of *Broussonetia papyrifera* fermented diet on growth performance, carcass quality and meat quality of xiangsha pigs commercial line of commercial pigs. Chinese Journal of Animal Nutrition, 2019; 31(12): 5760–5771. (in Chinese)

[5] He Y K, Li X Y, Ling H, Hu Z C, Tang S G, Yin Y L, et al. Effects of *Broussonetia papyrifera* silage on growth performance, nutrient apparent digestibility and intestinal health of mutton goats. Chinese Journal of Animal Nutrition, 2021; 33(9): 5131–5141. (in Chinese)

[6] Zhao X M, Liu J Y, Liu Y P, Liu Y P, Wang X, Jin J, et al. Effects of silage time of tender branches and leaves of *Broussonetia papyrifera* and feeding beef cattle on its growth performance and fattening benefits. Chinese Journal of Tropical Agriculture, 2022; 42(3): 51–56. (in Chinese)

[7] Geng D Y, Ji X Q, Mou X D, Li H B, Yang H L, Yao Y C, et al. Design and experiment of harvesting and cutting table of *Broussonetia papyrifera*. Journal of Jilin University (Engineering and Technology Edition), 2023; 53(7): 2152–2164. (in Chinese)

[8] Grima A P, Wypych P W. Development and validation of calibration methods for discrete element modelling. Granular Matter, 2011; 13(2): 127–132.

[9] Dai F, Song X F, Guo W J, Zhao W Y, Zhang F W, Zhang S L. Simulation and test on separating cleaning process of flax threshing material based on gas-solid coupling theory. Int J Agric & Biol Eng, 2020; 13(1): 73–81.

[10] Song Z H, Li ., Yan Y F, Tian F Y, Li Y D, Li F D. Calibration method of contact characteristic parameters of soil in mulberry field based on unequal-diameter particles DEM theory. Transactions of the CSAM, 2022; 53(6): 21–33. (in Chinese)

[11] Yu Q X, Liu Y, Chen X B, Sun K, Lai Q H. Calibration and experiment of simulation parameters for panax notoginseng seeds based on DEM. Transactions of the CSAM, 2020; 51(2): 123–132. (in Chinese)

[12] Wen X Y, Yuan H F, Wang G, Jia H L. Calibration method of friction coefficient of granular fertilizer by discrete element simulation. Transactions of the CSAM, 2020; 51(2): 115–122. (in Chinese)

[13] Shi Y Y, Xin (Rex) S, Wang X C, Hu Z C. David Newman, Ding W M. Numerical simulation and field tests of minimum-tillage planter with straw smashing and strip laying based on EDEM software. Computers and Electronics in Agriculture, 2019; 166: 105021.

[14] Wang Q R, Mao H P, Li Q L. Simulation of vibration response of flexible crop stem based on discrete element method. Transactions of the CSAM, 2020; 51(11): 131–137. (in Chinese)

[15] Ma Y H, Song C D, Xuan C Z, Wang H Y, Yang S, Wu P. Parameters calibration of discrete element model for alfalfa straw compression simulation. Transactions of the CSAE, 2020; 36(11): 22–30. (in Chinese)

[16] Shi R J, Dai F, Zhao W Y, Zhang F W, Shi L R, Guo J H. Establishment of discrete element flexible model and verification of contact parameters of flax stem. Transactions of the CSAM, 2022; 53(10): 146–155. (in Chinese)

[17] Liao Y T, Liao Q X, Zhou Y, Wang Z T, Jiang Y J, Liang F. Parameters calibration of discrete element model of fodder rape crop harvest in bolting stage. Transactions of the CSAM, 2020; 51(6): 73–82. (in Chinese)

[18] Ma Z, Li Y, Xu L. Discrete-element method simulation of agricultural particles' motion in variable-amplitude screen box. Computers and Electronics in Agriculture, 2015; 118: 92–99.

[19] Lenaerts B, De Ketelaere B, Tijskens E, Herman R, Baerdemaeker J D, Aertsen T, et al. Simulation of grain-straw separation by discrete element modeling with bendable straw particles. Computers and Electronics in Agriculture, 2014; 101: 24–33.

[20] Liu L, Wang X L, Zhang X C, Zhong X K, Wei Z C, Geng Y L, et al. Determination and verification of parameters for the discrete element modelling of single disc covering of flexible straw with soil. Biosystems Engineering, 2023; 233: 151–167.

[21] Ma S, Xu L M, Xu S, Tan H C, Song J F, Shen C C. Wear study on flexible brush-type soil removal component for removing soil used to protect grapevines against cold. Biosystems Engineering, 2023; 228: 88–104.

[22] Du Y Q, Ren F, Li Y, Xi H M, Wang Z, Wen F, et al. Effect of hybrid *Broussonetia papyrefera* silage on semen quality and feces microbial community of dairy goat. Acta ecologiae animalis domastici, 2022; 43(4): 55–59. (in Chinese)

[23] Wang L J, Liu T H, Feng X, Gao Y P, Wang B Zhang S. Research progress of the restitution coefficients of collision of particles in agricultural and food fields. Transactions of the CSAE, 2021; 37(20): 313–322. (in Chinese)

[24] Zhang X R, Hu X H, Liu J X, Yang Y M, Li Y. Calibration and verification of bonding parameters of banana straw simulation model based on discrete element method. Transactions of the CSAM, 2023; 54(5): 121–130. (in Chinese)