

CALIBRATION OF CONTACT PARAMETERS FOR RUMINANT PROTEIN SUPPLEMENT FEED PELLETS BASED ON THE DISCRETE ELEMENT METHOD

基于离散元的反刍动物蛋白补充饲料颗粒接触参数标定研究

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ABSTRACT

To address the limited research on the material properties of ruminant protein supplement feed pellets and the lack of an accurate calibration framework for discrete element method (DEM) contact parameters, which constrained the optimization of related mechanical equipment, this study investigated the fundamental physical and contact characteristics of protein supplement pellets. A DEM-based particle model was established, and the angle of repose was selected as the evaluation index. The Plackett–Burman design was employed to identify the primary influencing factors, followed by a Steepest Ascent test and a Box–Behnken design to develop a regression model for parameter optimization and calibration. The results indicated that when the static friction coefficient, rolling friction coefficient, and restitution coefficient between particles were set to 0.52, 0.03, and 0.37, respectively, the restitution coefficient between particles and materials, as well as the static and rolling friction coefficients between particles, had significant effects on the angle of repose. The optimal parameter values were determined to be 0.45, 0.55, and 0.05, achieving the theoretical optimum. Validation experiments showed that the average deviation between the calibrated and measured angles of repose was 0.92%, demonstrating a high level of agreement between the simulated and experimental results. These findings provided a reliable theoretical reference and parameter basis for the optimization of processing, conveying, and key component design in ruminant protein supplement feed machinery.

摘要

针对反刍动物蛋白补充饲料颗粒物料特性研究不足、离散元仿真实接触参数标定体系不完善、难以为相关机械装备优化设计提供可靠理论与数据支撑的问题，本研究以蛋白补充颗粒饲料为研究对象，开展了基本物理特性与接触特性测试。基于离散元方法构建颗粒仿真模型，以休止角为评价指标，采用 Plackett Burman 试验筛选主要影响因素，进一步结合最陡爬坡试验与 Box Behnken 设计建立回归模型，实现了仿真实接触参数的优化标定。结果表明，当颗粒与材料的静摩擦系数、滚动摩擦系数及颗粒间碰撞恢复系数分别为 0.52、0.03 和 0.37 时，颗粒与材料的碰撞恢复系数以及颗粒间静摩擦系数、滚动摩擦系数对休止角的影响显著；其最优取值分别为 0.45、0.55 和 0.05，模型达到理论最优解。验证试验结果显示，标定后休止角与实测值的平均误差为 0.92%，表明仿真结果与试验结果具有较高一致性。研究成果可为反刍动物蛋白补充饲料在加工、输送及相关机械关键部件的优化设计提供可靠的理论参考与参数支持。

INTRODUCTION

With the continuous development of large-scale and intensive animal husbandry, ruminants have an increasing demand for efficient and balanced nutrition. As a key component of the daily diet, the quality and performance of protein supplement feed pellets directly affect animal health, growth, and productivity (Zhang, 2025; Fang et al., 2022). The physical and mechanical properties of pelleted feed have a significant influence on its flowability and stability during processing, storage, transportation, and feeding (Choct, 2006). Therefore, systematically and accurately characterizing the material properties of protein supplement feed pellets is of great theoretical and practical importance for improving feed utilization efficiency and optimizing the design of related mechanical equipment.

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In recent years, the Discrete Element Method (DEM) has become an effective computational approach for investigating the motion behavior and interaction mechanisms of granular materials, and has been widely applied in agricultural engineering, food processing, and bulk material handling (Rackl & Hanley, 2017; Zhao *et al.*, 2024; Bu *et al.*, 2023). DEM simulations enable in-depth analysis of particle flow and accumulation under various operational conditions, providing quantitative insights that are often difficult to obtain experimentally (Yang *et al.*, 2023; Mi *et al.*, 2022). Numerous studies have successfully combined bench-scale experiments and DEM simulations to calibrate particle parameters and analyze the flow or pile behavior of granular crops such as corn and soybeans (Wen *et al.*, 2024; Chen *et al.*, 2024). A few investigations have extended these methods to feed pellets, attempting to model their collective flow behavior or fracture mechanisms (Xu, 2021; Wang *et al.*, 2024; Zhou *et al.*, 2018). Nevertheless, existing research has predominantly focused on agricultural grains or single-component feed materials. Systematic studies on ruminant protein supplement feed pellets remain scarce, especially concerning the accurate calibration of DEM contact parameters that govern energy dissipation, frictional resistance, and collision restitution during particle interactions. Because the predictive reliability of DEM simulations critically depends on the precision of these contact parameters, inadequate calibration hinders the application of DEM in optimizing feed-processing and conveying systems (Yang *et al.*, 2024; Wang *et al.*, 2024). This gap underscores the necessity for a quantitative calibration framework linking measurable physical properties with accurate DEM simulation parameters.

In this context, this study focused on ruminant protein supplement feed pellets to establish a comprehensive DEM calibration framework grounded in measured physical characteristics. Specifically, the objectives of this work were to: (1) systematically determine the basic physical properties of the pellets, including particle geometry, density, and frictional parameters; (2) develop and calibrate a DEM model using the angle of repose as the evaluation index through a combination of Plackett–Burman screening, Steepest Ascent, and Box–Behnken designs; and (3) validate the accuracy and applicability of the calibrated contact parameters through experimental comparison. The central hypothesis of this study was that accurately calibrated DEM contact parameters, derived from measurable physical characteristics, can reliably reproduce the macroscopic flow and accumulation behavior of ruminant feed pellets, thereby providing a theoretical and parametric foundation for the optimization of feed processing, conveying, and key mechanical components.

MATERIALS AND METHODS

Fundamental characteristics of feed pellets

The research object in this study was a protein supplement feed pellet formulated specifically for ruminants, as illustrated in Figure 1. The main ingredients of the feed included soybean meal, rapeseed meal, and corn, with minor additions of fish meal and minerals. The pellets exhibited a relatively uniform rectangular shape. To accurately characterize the geometric morphology of the pellets, three-dimensional geometric dimensions - length (L), width (W), and thickness (T) - were measured. A total of 100 pellet samples were randomly selected, and each dimension was measured three times to obtain an average value. The average length, width, and thickness of the pellets were 6.18 mm, 6.34 mm, and 3.41 mm, respectively. The pellet density was determined by the displacement method, yielding a value of 1.33 g/cm³. The fundamental physical properties of the feed pellets are summarized in Table 1.

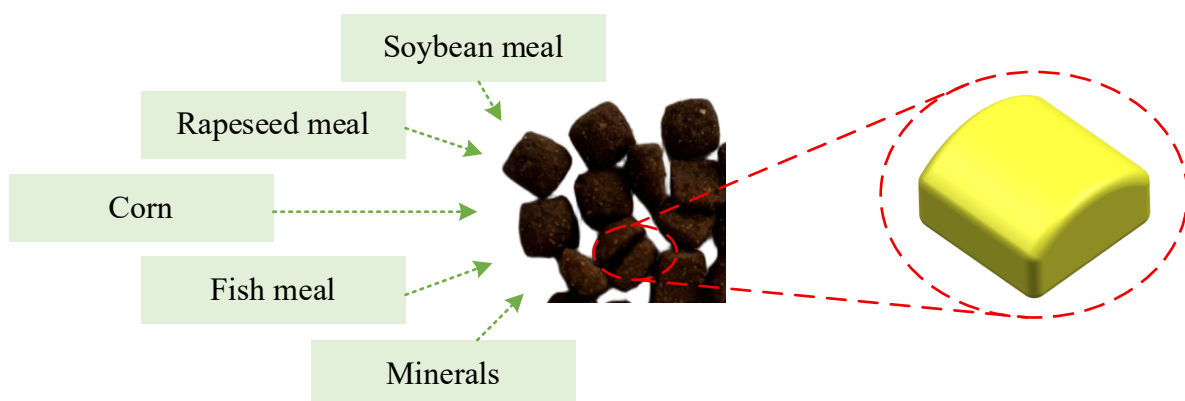


Fig. 1 – Protein supplement feed pellet

Table 1

Intrinsic parameter settings							
Item	Length / mm		Width / mm		Height / mm		Density / (g cm ⁻³)
	Mean	SD	Mean	SD	Mean	SD	
Feed pellets	6.18	0.15	6.34	0.20	3.41	0.22	1.33

Contact characteristics of feed pellets

Considering the granular characteristics of the feed pellets, measurements were conducted to determine their angle of repose, friction coefficient, restitution coefficient, and Poisson's ratio.

Angle of repose

The angle of repose refers to the angle formed between the natural slope of a freely accumulated pile of particles and the horizontal plane under static conditions. It serves as an important parameter reflecting the flowability of granular materials. The angle of repose of feed pellets directly affects their flow behavior and stability during processing, transportation, and storage.

In this study, the funnel method was employed to measure the angle of repose of the feed pellets. A uniform sample of feed pellets was slowly poured through a funnel at a constant rate onto a 304 stainless-steel plate, allowing the particles to form a conical pile naturally. A side view of the pile was photographed using a digital camera, and the captured images were processed in MATLAB through grayscale conversion, binarization, boundary extraction, and linear fitting to determine the slope angle between the pile surface and the horizontal plane. All measurements were conducted under controlled laboratory environmental conditions, with a temperature of $25\pm1^\circ\text{C}$ and a relative humidity of $50\pm5\%$. The measurement procedure and image-processing workflow are illustrated in Fig. 2. Each test was repeated five times, and the average value was recorded as the final result. The measured angle of repose of the feed pellets was 28.27° .

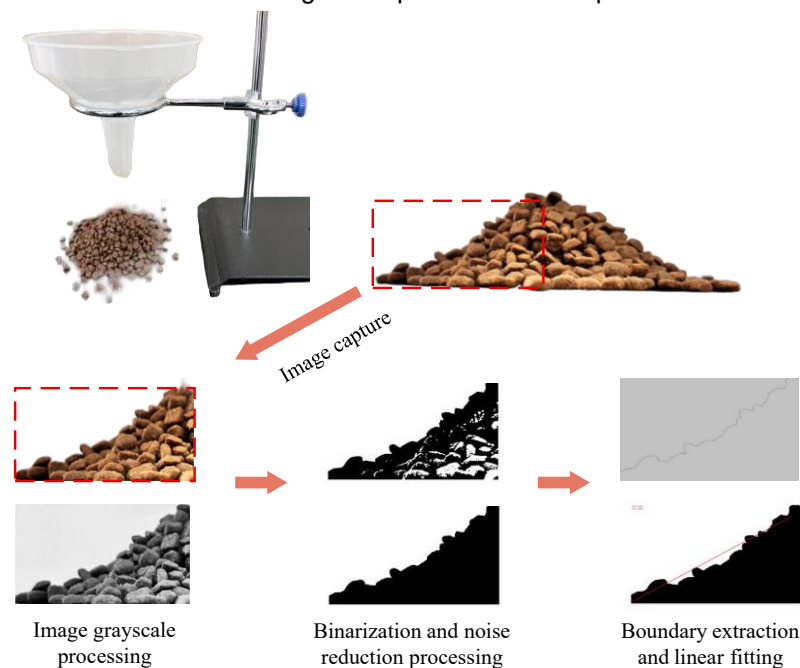


Fig. 2 – Measurement of the angle of repose and image processing procedure

Coefficient of friction

The coefficient of friction is one of the key parameters describing the interaction forces between the surfaces of granular materials. It plays an essential role in determining the behavior of particles during processing, storage, and conveying. The friction coefficient of feed pellets directly affects their flowability and packing stability.

In this study, a friction coefficient measurement apparatus was used to determine the static and rolling friction coefficients between feed pellets and between feed pellets and 304 stainless-steel plates. The measurement procedure for the static friction coefficient was as follows: the flat plate was placed horizontally, a sample of feed pellets was positioned on its surface, and the plate was slowly inclined until the pellets began to slide. The inclination angle at the onset of motion was recorded as α_1 , as shown in Fig. 3(a). The static friction coefficient (f_1) was then calculated using the equation $f_1 = \tan(\alpha_1)$.

The rolling friction coefficient was determined using the energy method. Spherical feed pellets with high sphericity and identical composition were selected, with an equivalent rolling radius of r . The measurement procedure was consistent with that of the static friction coefficient. The critical inclination angle at which rolling began, denoted as α_2 , was recorded as shown in Fig. 3(b). The rolling friction coefficient (f_2) was calculated using the equation $f_2 = r \cdot \tan(\alpha_2)$. Similarly, by spreading a uniform layer of feed pellets over the plate surface and repeating the same procedure, the static and rolling friction coefficients between feed pellets were obtained. The results of the friction coefficient measurements are summarized in Table 2.

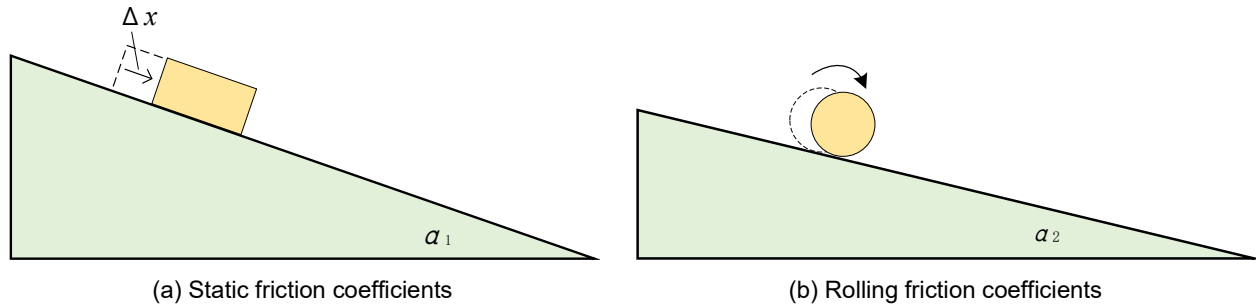


Fig. 3 – Measurement of the friction coefficient

Table 2

Measured friction characteristics of feed pellets

Item	Static friction coefficients	Rolling friction coefficients
Pellet-pellet	0.45-0.75	0.02-0.08
Pellet-304 stainless steel	0.38-0.65	0.01-0.05

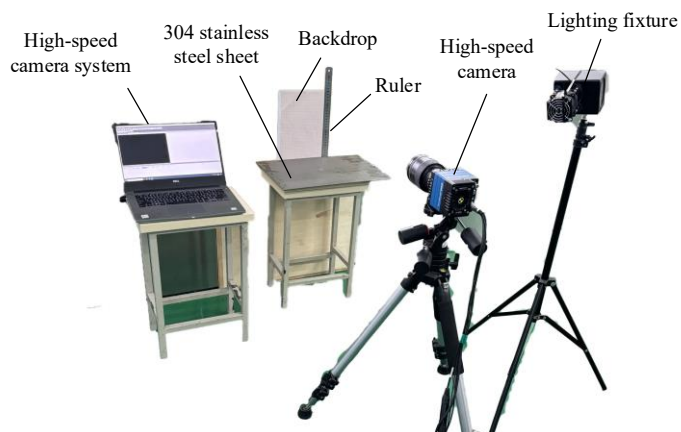
Coefficient of restitution

The coefficient of restitution is an important parameter that characterizes the energy loss during particle collisions and reflects the ability of a particle to recover its velocity after impact (Huang *et al.*, 2014; Feng *et al.*, 2017). It directly affects the dynamic behavior of feed pellets during processing, conveying, and mixing operations.

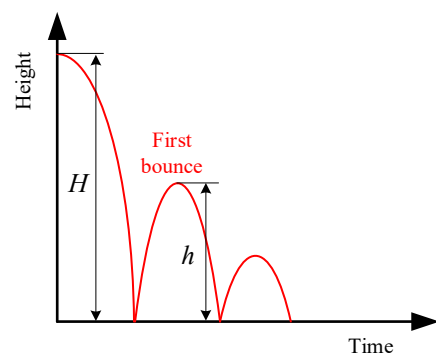
In this study, the coefficient of restitution between feed pellets and between feed pellets and 304 stainless-steel plates was measured using the free-fall method. The experimental setup is illustrated in Fig. 4(a), consisting of a high-speed camera, illumination source, backdrop panel, and a 304 stainless-steel plate positioned at the bottom. The procedure was as follows: the backdrop was placed vertically, and the stainless-steel plate was set horizontally beneath it. The high-speed camera was adjusted to an appropriate position, and a single feed pellet was released from a fixed height to fall freely onto the stainless-steel surface. The falling and rebounding processes were recorded, as shown in Fig. 4(b). The coefficient of restitution (e) was calculated using Equation (1):

$$e = \sqrt{\frac{h}{H}} \quad (1)$$

where: H is dropping height of the feed pellet, mm; h is rebound height of the feed pellet, mm.



(a) Measurement apparatus



(b) Measurement principle

Fig. 4 – Measurement of the coefficient of restitution of feed pellets

Table 3

Measured coefficients of restitution of feed pellets

Item	Coefficient of restitution
Pellet-pellet	0.32-0.41
Pellet-304 stainless steel	0.39-0.49

Coefficient of restitution

Poisson's ratio is a dimensionless parameter that describes the ratio between the transverse strain and axial strain of a material, serving as an important indicator of its elastic and deformation characteristics. For granular materials such as feed pellets, Poisson's ratio reflects their ability to undergo volumetric changes under loading conditions.

In this study, the Poisson's ratio of feed pellets was determined using a compression test, as shown in Fig. 5. The testing system mainly consisted of a universal testing machine, a displacement control device, and a measurement setup. The procedure was as follows: markers were placed on the lateral surface of each feed pellet, and the initial radial distance between the markers was recorded. The pellet was then placed on the lower platen of the testing machine, with a compression speed set at 3 mm/min and a displacement of 2 mm. Without unloading the compression force, the radial distance between the markers was measured again. The Poisson's ratio (ν) was calculated using Equation (2):

$$\nu = \left| \frac{\varepsilon_1}{\varepsilon_2} \right| = \left| \frac{(W_1 - W_2) / W_1}{(L_1 - L_2) / L_1} \right| \quad (2)$$

where: ν is Poisson's ratio; ε_1 is the transverse strain of the marked diameter; ε_2 is the axial strain of the pellet length; L_1 and L_2 are the pellet lengths before and after compression, mm; W_1 and W_2 are the marked cross-sectional diameters before and after compression, mm.

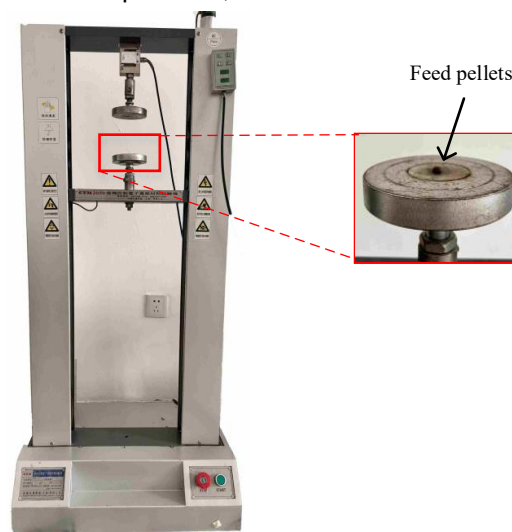


Fig. 5 – Apparatus and principle for measuring the Poisson's ratio of feed pellets

Discrete element method

The Discrete Element Method (DEM) is a numerical simulation approach widely used in studying the behavior of granular materials. By simulating the interactions among particles, DEM can accurately describe both the macroscopic motion and the microscopic mechanical behavior of granular systems. The contact model serves as the core of DEM, determining the force transmission and motion characteristics between particles. In this study, an appropriate contact model was selected based on the physical characteristics of the feed pellets to perform the simulation analysis.

The selection of a contact model should be determined according to the specific simulation conditions and particle properties. Based on the physical attributes of the feed pellets, the Hertz–Mindlin (no slip) contact model was adopted in this study. In this model, each particle possesses six degrees of freedom, including three translational and three rotational motions. Therefore, both translational and rotational dynamics must be considered. The fundamental principle of DEM is to apply Newton's second law to calculate the translational and angular accelerations of particles, and then perform numerical integration within each time step to update their velocity and position. The basic governing equations are given in Equations (3) and (4):

$$\begin{cases} x(t + \Delta t) = x(t) + v(t)\Delta t \\ v(t + \Delta t) = v(t) + a(t)\Delta t \end{cases} \quad (3)$$

$$\begin{cases} I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_i} (T_i + T_r) \\ m_i \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{n_i} (F_n + F_{nI} + F_t + F_{tI}) \end{cases} \quad (4)$$

where: $x(t)$ is the position of the particle; $v(t)$ is the particle velocity; $a(t)$ is the acceleration of the particle at time t ; Δt is the simulation time step; m_i , v_i , ω_i , and I_i represent the particle mass, translational velocity, angular velocity, and moment of inertia, respectively; n_i is the number of contacts between particle i and particle j ; F_{nI} and F_n are the normal damping force and normal contact force, respectively; F_{tI} and F_t are the tangential damping force and tangential contact force, respectively; T_i and T_r are the tangential torque and rolling friction torque, respectively.

RESULTS AND DISCUSSIONS

Particle model construction

In performing the discrete element method (DEM) simulation of the angle of repose for feed pellets, it is essential to establish a representative particle model. Based on the target geometry and the measured three-axis dimensions of the feed pellets, the particle model was generated using the Auto-fill function in EDEM.

First, a three-dimensional model of the feed pellet was created in a CAD software according to the measured geometric dimensions and exported in .stp format. This file was then imported into EDEM as a particle-filling template, where the visualized mesh contour served as the boundary reference for automatic particle filling, as shown in Fig. 6(a). After importing the contour, the auto-fill parameters were configured. To balance model accuracy and computational efficiency, the grid cell numbers in the x, y, and z directions were each set to 30, the minimum particle radius was defined as 0.5 mm, and the smoothing value was set to 5. The final filled feed pellet model is shown in Fig. 6(b).



(a) Filling boundary



(b) Filling result

Fig. 6 - Particle filling process

In DEM simulations, the rational and accurate setting of particle parameters is a critical factor influencing the simulation results. In the parameter calibration of the angle of repose simulation, the basic physical parameters of the feed pellets were configured as listed in Table 4. To investigate the influence of contact mechanical parameters on the simulated angle of repose, a parameter calibration test was conducted using contact parameters as experimental factors. To minimize the number of simulation runs while efficiently identifying significant factors, a Plackett-Burman design was employed with the angle of repose as the evaluation index.

Table 4

Basic physical parameters of particles and geometry for parameter calibration simulation

Parameter	Feed pellets	304 stainless steel
Poisson's ratio	0.35	0.3
Shear modulus / (MPa)	1.45	7.7×10^4
Density / ($\text{g} \cdot \text{cm}^{-3}$)	1.33	7.93

Six factors were selected for the experimental design: the static friction coefficient between pellets, the static friction coefficient between pellets and 304 stainless steel, the rolling friction coefficient between pellets, the rolling friction coefficient between pellets and 304 stainless steel, the restitution coefficient between pellets, and the restitution coefficient between pellets and 304 stainless steel. The maximum and minimum levels of each variable were coded as +1 and -1, respectively, as shown in Table 5.

Table 5

Basic physical parameters of particles and geometry for parameter calibration simulation

Parameter	Level	
	-1	1
Static friction coefficient between particle and material (A)	0.38	0.65
Rolling friction coefficient between particle and material (B)	0.01	0.05
Restitution coefficient between particle and material (C)	0.39	0.49
Static friction coefficient between particles (D)	0.45	0.75
Rolling friction coefficient between particles (E)	0.02	0.08
Restitution coefficient between particles (F)	0.32	0.41

The simulated angle of repose was measured using the funnel method, following the same procedure as in the physical experiments, with a simulation duration of 3 s. The simulated angle of repose, denoted as θ_1 , was determined by measuring the pile angles in the front, rear, left, and right directions, and the average value was taken as the final result. The Plackett-Burman experimental design and results are presented in Table 6, while the significance and t-test analyses of factor effects are summarized in Table 7 and Fig. 7.

Table 6

Plackett-Burman experimental design and results

No.	A	B	C	D	E	F	Angle of repose θ_1
1	1	1	-1	1	1	1	29.35
2	-1	1	1	-1	1	1	27.66
3	1	-1	1	1	-1	1	31.70
4	-1	1	-1	1	1	-1	28.57
5	-1	-1	1	-1	1	1	25.94
6	-1	-1	-1	1	-1	1	27.37
7	1	-1	-1	-1	1	-1	24.26
8	1	1	-1	-1	-1	1	18.53
9	1	1	1	-1	-1	-1	19.75
10	-1	1	1	1	-1	-1	27.94
11	1	-1	1	1	1	-1	32.62
12	-1	-1	-1	-1	-1	-1	21.60

Table 7

Significance test results of the Plackett-Burman experiment

Source of variation	Sum of squares	df	Mean square	F value	P value	Significant
Model	206.66	6	34.44	14.08	0.0054**	Significant
A	0.69	1	0.69	0.28	0.6190	
B	11.39	1	11.39	4.66	0.0834	
C	21.15	1	21.15	8.65	0.0322*	Significant
D	132.07	1	132.07	54.00	0.0007**	Significant
E	38.56	1	38.56	15.76	0.0106*	Significant
F	2.81	1	2.81	1.15	0.3325	
Residual	12.23	5	2.45			
Total	218.89	11				
R^2	0.9441		Pred- R^2		0.6782	
Adj- R^2	0.8771		Adeq Precision		11.599	

As shown in Table 7, the P-value of the model is 0.0054 (<0.05), indicating that the model is statistically significant and exhibits a good fit within the studied regression region, confirming its reliability. The significant factors identified in the model are the restitution coefficient between particles and material (C), the static friction coefficient between particles (D), and the rolling friction coefficient between particles (E). The coefficient of determination (R^2) is 0.9441, indicating a high degree of correlation, while the adjusted coefficient of determination (Adj- R^2) is 0.8771, suggesting that 87.71% of the variation in the experimental data can be explained by the regression model. The adequate precision, representing the signal-to-noise ratio, is 11.599, which is greater than 4.0, implying that the signal is adequate and the model has satisfactory predictive capability and stability.

The regression equation obtained through multiple regression fitting is expressed as follows:

$$\theta_1 = -1.77A - 48.71B + 26.55C + 22.12D + 59.75E + 10.76F - 1.72 \quad (5)$$

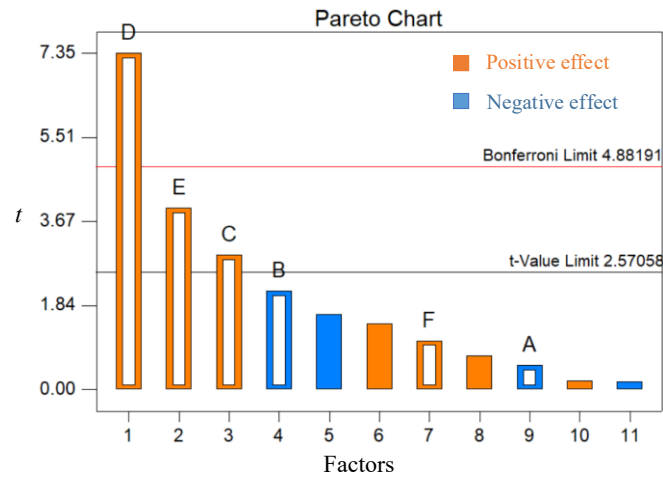


Fig. 7 – Pareto chart of the angle of repose

Steepest ascent experiment

According to the results of the Plackett–Burman design, the static friction coefficient between particles and material (A), the rolling friction coefficient between particles and material (B), and the restitution coefficient between particles (F) had no significant influence on the simulated angle of repose. Therefore, their values were fixed at 0.52, 0.03, and 0.37, respectively. The significant factors selected for further optimization were the restitution coefficient between particles and material (C), the static friction coefficient between particles (D), and the rolling friction coefficient between particles (E), with initial values of 0.39, 0.45, and 0.02, respectively. The step sizes for these factors were set as 0.02, 0.06, and 0.01.

Based on the significance analysis, a Steepest Ascent experiment was conducted to identify the direction and range of the optimal parameter combination approaching the true values. The results of this experiment were used to determine the center points for the subsequent Box–Behnken optimization design. The experimental design and results of the Steepest Ascent test are presented in Table 8.

Table 8

Experimental design and results of the Steepest Ascent test

No.	C	D	E	Angle of repose θ_r / (°)	Relative error δ / (%)
1	0.39	0.45	0.02	25.04	11.43
2	0.41	0.51	0.03	25.91	8.35
3	0.43	0.57	0.04	26.52	6.19
4	0.45	0.63	0.05	27.17	3.89
5	0.47	0.69	0.06	29.95	5.94
6	0.49	0.75	0.07	30.2	6.83

Box-Behnken experimental design and results

Based on the results of the Steepest Ascent experiment, the parameter combination of Run 4 was selected as the zero level, while those of Run 2 and Run 6 were designated as the –1 and +1 levels, respectively, for the Box–Behnken experiment. The coded factor levels are listed in Table 9. The experimental design and results are shown in Table 10, and the analysis of variance (ANOVA) results are summarized in Table 11.

Table 9

Coded factor levels in the Box-Behnken design

Level	C	D	E
-1	0.49	0.75	0.07
0	0.45	0.63	0.05
+1	0.41	0.51	0.03

Table 10

Experimental design and results of the Box-Behnken test

No.	C	D	E	Angle of repose θ_r / (°)
1	-1	-1	0	24.47
2	1	-1	0	25.21
3	-1	1	0	25.51
4	1	1	0	30.88

No.	C	D	E	Angle of repose θ_r / (°)
5	-1	0	-1	25.36
6	1	0	-1	27.82
7	-1	0	1	28.17
8	1	0	1	29.96
9	0	-1	-1	25.07
10	0	1	-1	29.38
11	0	-1	1	27.24
12	0	1	1	30.21
13	0	0	0	27.92
14	0	0	0	28.59
15	0	0	0	28.09
16	0	0	0	28.73
17	0	0	0	28.38

Table 11

Significance test results of the Plackett-Burman experiment

Source of variation	Sum of squares	df	Mean square	F value	P value	Significant
Model	57.06	9	6.34	36.92	< 0.0001	Significant
C	12.05	1	12.05	70.19	< 0.0001	Significant
D	22.71	1	22.71	132.27	< 0.0001	Significant
E	2.83	1	2.83	16.49	0.0048	Significant
CD	4.18	1	4.18	24.35	0.0017	Significant
CE	0.11	1	0.11	0.65	0.4455	Not significant
DE	0.43	1	0.43	2.5	0.158	Not significant
C ²	13.78	1	13.78	80.21	< 0.0001	Significant
D ²	0.33	1	0.33	1.91	0.21	Not significant
E ²	0.13	1	0.13	0.78	0.4055	Not significant
Residual	1.2	7	0.17			
Lack of fit	0.59	3	0.2	1.29	0.3919	Not significant
Error	0.61	4	0.15			
Total	58.26	16				

According to the results of the analysis of variance (ANOVA), the regression model for the angle of repose of feed pellets was highly significant ($P < 0.0001$), whereas the lack-of-fit term was not significant ($P = 0.3919$), indicating a good overall fit of the model. The restitution coefficient between particles and material (C), the static friction coefficient between particles (D), the rolling friction coefficient between particles (E), the interaction term between C and D (CD), and the quadratic term of C (C^2) had significant effects on the simulated angle of repose θ_r .

After eliminating the non-significant terms, the regression model for the significant factors affecting the angle of repose was established as follows:

$$\theta_r = 928.20C - 81.82D + 29.75E + 213.02CD - 1146.35C^2 - 165.06 \quad (6)$$

Using the mean measured angle of repose (28.27°) from physical experiments as the target value, the regression model was optimized to obtain the best combination of parameters: restitution coefficient between particle and material $C = 0.45$, static friction coefficient between particles $D = 0.55$, and rolling friction coefficient between particles $E = 0.05$. Substituting these values into the model yielded a theoretical angle of repose of 28.2699° , with a minimal relative error compared with the experimental value, indicating that the developed regression model can accurately predict the angle of repose of feed pellets.

Verification experiment

Based on the parameter calibration results, the final calibrated contact parameters for the DEM simulation of feed pellets are listed in Table 12. To verify the accuracy of the calibrated parameters, a validation simulation was conducted using the optimized contact parameter set. The comparison between the simulated and experimentally measured pellet pile configurations is shown in Fig. 8.



Fig. 8 – Comparison between simulated and actual particle pile configurations

Table 12

Calibrated contact parameters for DEM simulation

Parameter	Value
Static friction coefficient between particle and material (A)	0.52
Rolling friction coefficient between particle and material (B)	0.03
Restitution coefficient between particle and material (C)	0.45
Static friction coefficient between particles (D)	0.55
Rolling friction coefficient between particles (E)	0.05
Restitution coefficient between particles (F)	0.37

The verification test was repeated five times, yielding a simulated angle of repose of 28.53°. The average relative error between the simulated and measured angles of repose was 0.92%, and the deviation in each individual test was less than 1%. These results demonstrate that the established DEM contact parameter calibration method provides high accuracy and reproducibility.

The obtained results were consistent with general findings reported for similar granular materials such as feed pellets, seeds, and food grains, indicating that the calibrated parameters can effectively capture the macroscopic flow and accumulation behavior of ruminant protein supplement pellets. However, certain limitations should be noted. The Hertz–Mindlin (no slip) contact model used in this study assumes purely elastic and non-adhesive particle interactions, which may not fully account for surface roughness, particle deformation, or cohesion effects that occur in real materials. Despite these simplifications, the model provided a reasonable balance between computational efficiency and accuracy, and the overall agreement between simulation and experiment confirmed the reliability of the proposed calibration method.

CONCLUSIONS

In this study, protein-supplemented feed pellets for ruminants were selected as the research object to investigate their material properties and to calibrate the discrete element contact parameters. The main conclusions are as follows:

(1) The geometric and physical characteristics of the selected feed pellets were determined. The average length, width, and height were 6.18 mm, 6.34 mm, and 3.41 mm, respectively, with a density of 1.33 g/cm³. The measured angle of repose using the funnel method was 28.27°. The static friction coefficient, rolling friction coefficient, and restitution coefficient between pellets ranged from 0.45–0.75, 0.02–0.08, and 0.32–0.41, respectively. The corresponding values between pellets and 304 stainless steel ranged from 0.38–0.65, 0.01–0.05, and 0.39–0.49, respectively. The Poisson's ratio was measured as 0.35 using a compression tester.

(2) Based on the measured material properties, a DEM simulation model of the feed pellets was constructed in EDEM, and parameter calibration was conducted. A Plackett–Burman design was employed with the angle of repose as the evaluation index to identify the significant parameters, namely the restitution coefficient between particle and material, the static friction coefficient between particles, and the rolling friction coefficient between particles. Subsequently, a regression model of the angle of repose was established and optimized through the Steepest Ascent and Box–Behnken designs. The model achieved the theoretical optimum when the static and rolling friction coefficients between particle and material and the restitution coefficient between particles were 0.52, 0.03, and 0.37, respectively, while the restitution coefficient between particle and material, static friction coefficient, and rolling friction coefficient between particles were 0.45, 0.55, and 0.05.

(3) To verify the accuracy of the calibrated contact parameters, validation tests of the angle of repose were performed using the optimized parameter set. The simulated angle of repose was 28.53°, with an average relative error of only 0.92% compared with the measured value, and all individual test deviations were less than 1%. These findings confirm that the established calibration method is accurate and reliable, providing theoretical and data support for feed pellet processing, conveying, and equipment design.

This study focused on a specific type of protein-supplemented feed pellets, and the proposed methodology provides a theoretical and methodological basis for future studies. However, the influence of feed formulation, environmental conditions, and particle morphology on the contact characteristics should be further explored. Future research will investigate how particle shape, size distribution, and composition variations affect the calibration and accuracy of DEM contact parameters.

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