

Article

An Investigation on a Comprehensive Calibration Technique to Determine the Discrete Elemental Characteristics of Unrotted Sheep Dung at Varying Water Concentrations

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Abstract: An experimental study was undertaken to investigate the problem of the substantial variability in water content in unrotted sheep dung, which leads to a lack of universality and practicality in calibrating its discrete element simulation parameters. The stacking angle was used as the response value in these experiments. The objective of this study was to establish precise simulation parameters for the composting process. A model for water content-stacking angle was established using the cylinder-lifting technique, resulting in a correlation value of 0.997. Utilizing the Hertz–Mindlin with JKR bonding model, three EDEM particle models were developed, each with distinct particle sizes, based on the particle size distribution of sheep dung. The JKR surface energy was determined using the Plackett–Burman test, the steepest-climbing test, and the Box–Behnken test using a set of 10 parameters. A subsequent study was conducted on the JKR surface energy, rolling friction factor, and static friction factor utilizing the Plackett–Burman test and Box–Behnken test. A parameter model for stacking angle–discrete elements was developed that achieved a *p*-value below 0.0001 and a relative inaccuracy of 3.46% or less. The regression model for the water content–discrete element parameter was derived by combining the water content–stacking angle model with the stacking angle–discrete element parameter model. Validation of this model was conducted using both the pumping plate technique and the hopper approach, resulting in a relative error of 4.89% or less. The findings demonstrate that the specific characteristics of sheep manure may be accurately anticipated by considering its water content. This approach offers a valid and universally applicable way of predicting the specific characteristics of sheep dung in the simulation of composting equipment.

Keywords: unrotted sheep manure; moisture content; discrete element; EDEM; calibration; stacking angle



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1. Introduction

The Inner Mongolia Autonomous Region is characterized by vast natural grasslands and abundant resources for sheep farming, creating ideal conditions for large-scale sheep production [1–4]. As one of the regions with the largest sheep population in China, Inner Mongolia plays a significant role in global mutton production [5–8]. However, the mismanagement of manure from large-scale sheep farming poses serious environmental risks [9,10]. Consequently, China is actively promoting organic fertilizers as a sustainable alternative to chemical fertilizers [11–13]. Goat manure from Inner Mongolia is considered a valuable resource due to its high organic matter content (40–65%) and low levels of pollutants, such as antibiotics [14]. Compared to other livestock manures, including cow, horse, pig, and poultry manure, goat manure demonstrates a higher organic content, making it well-suited

for practical application [15,16]. Organic fertilizers produced from goat manure can enhance soil microbial activity, fertility, structure, and nutrient levels, thus contributing to a more favorable ecological environment [11,17–22]. Therefore, composting sheep manure into organic fertilizer not only aligns with national policies but also meets the needs of agricultural practices.

To enhance the efficiency of converting sheep manure into organic fertilizer, a compact, ventilated, and heated composting system (illustrated in Figure 1) was designed and developed [23–25]. Field trials demonstrated that the system effectively promotes the production of organic fertilizer; however, an uneven mixing issue was identified during the experiment, resulting in inconsistent composting outcomes. To improve compost quality, it is essential to optimize the design of the mixing blades in the composting equipment, ensuring proper mixing of the goat manure to achieve complete composting and enhance operational efficiency. Consequently, employing simulation software is necessary to obtain accurate parameters and facilitate the successful implementation of equipment simulation.

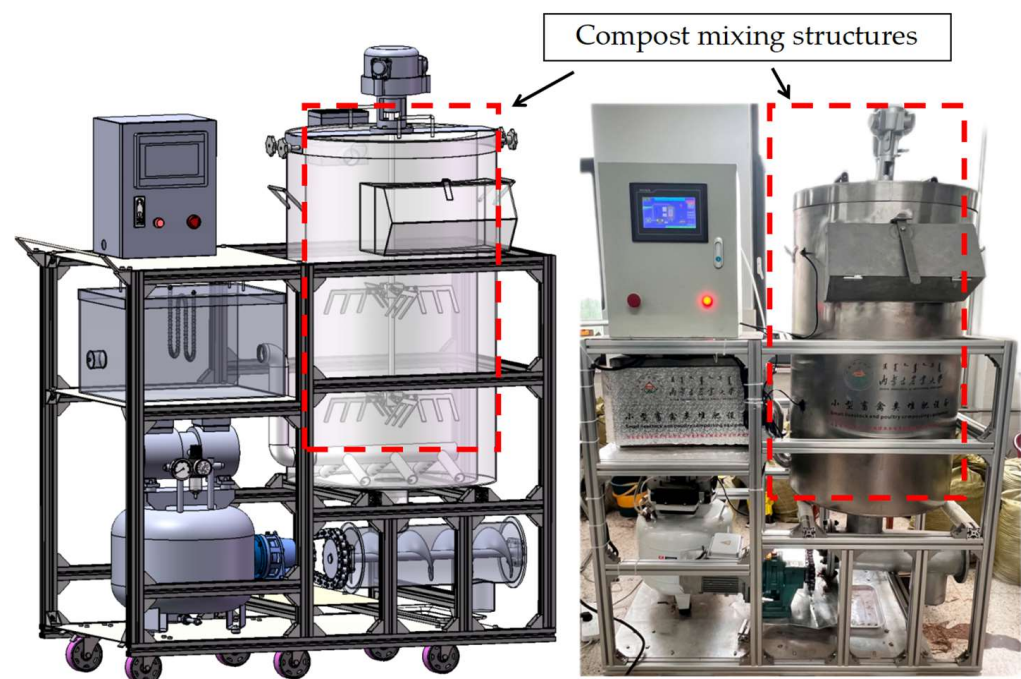


Figure 1. Compost mixer.

Given the advances in computer technology, the discrete element method (DEM) is extensively applied in the study of agricultural equipment [26–28]. The DEM is a systematic approach utilized to analyze the interactions between bulk materials and mechanical devices aimed at enhancing design and operating parameters [29,30]. This method has demonstrated significant improvements in research productivity, device performance, and cost-effectiveness [31]. Therefore, refining the discrete element properties of materials is essential for understanding the interactions between materials and devices [32–36].

In this context, developing a flexible and pragmatic discrete element parameter model for our study of sheep dung becomes crucial. The aim of this model is to optimize the performance of composting equipment by providing insights for improving mixing blades. For example, Yuan et al. employed the cylinder-lifting technique to investigate organic fertilizer particles derived from sheep dung [37]. Similarly, Luo et al. explored the parametric characteristics of vermicompost manure substrate, emphasizing water activity [38]. Additionally, through a combination of physical stacking experiments and discrete element simulations, Wang et al. calibrated the microscopic contact characteristics of pig dung [39]. Furthermore, Wen and colleagues accurately determined the friction coefficients between urea particles and PVC materials, as well as among the particles themselves [40]. Lin et al. also examined

the parametric characteristics of vermicompost particles, specifically focusing on water content [41]. Moreover, Han et al. investigated the parameterization of discrete element simulations for bulk stable manure used in orchards in Xinjiang [42]. Lastly, Zhu Xinhua et al. utilized the cylinder-lifting technique to investigate the characteristics of decomposing sheep dung [43].

There have been various calibration studies on animal manure both domestically and internationally; however, there is a notable absence of parameter calibration studies specifically focused on unrotted sheep manure. This gap hinders the development of an accurate mathematical model for the treatment of sheep manure using the mixing blades of a composting device. To address these issues, this study examines unrotted sheep manure with a moisture content ranging from 30.66% to 58.63%. The aim is to investigate the challenges associated with moisture content and rest angle throughout the composting process.

- (1) Establishment of two related mathematical models: Using the hollow cylinder lifting method, a moisture content–stacking angle model was established. A discrete element–stacking angle model was established using the EDEM 2022 simulation software, including Plackett–Burman testing, steepest ascent testing, and Box–Behnken experimental design.
- (2) Coupled mathematical model: By combining the moisture content–stacking angle model with the discrete element–stacking angle model, a moisture content–discrete element parameter model was constructed. This model can directly obtain key discrete element simulation parameters from the moisture content of unrotted sheep manure, providing an accurate mathematical model for the simulation of the mixing process of sheep manure in composting equipment.
- (3) Model validation: The reliability of the developed model was verified by pumping plate and funnel experiments, which confirmed its accuracy in calibrating the discrete element parameters of sheep manure.
- (4) Research contribution: The calibration method established in this study provides a flexible and effective way to optimize composting equipment. The mathematical model improves the accuracy of mechanical equipment simulation and helps to improve the design and operation of composting machinery.

2. Materials and Methods

2.1. Test Material and Particle Size Distribution

Sheep dung that had not yet decomposed was collected from a fertilizer-processing facility in Salazi Town, Tumet Right Banner, Baotou City, Inner Mongolia Autonomous Region. The initial moisture content was determined to be 42.34%, and the density was measured at 0.42 g/cm³ using the JDARK 485 Soil Tester and TM-85 Soil Density Meter. The fresh sheep dung was then subjected to natural air-drying, resulting in air-dried sheep manure with a moisture content of 14.12% and a density of 0.18 g/cm³, as shown in Figure 2. To investigate the impact of moisture content, five moisture content gradients were created by adding pure water [44].

$$m_s = \frac{m_0}{1 - \omega_0} (\omega_1 - \omega_0) \quad (1)$$

where m_s represents the mass of water added to the configured sheep manure sample (kg); m_0 represents the mass of the sheep manure sample (kg), ω_0 represents the original moisture content (%), and ω_1 represents the target moisture content of the configured sheep manure sample (%).

To estimate the moisture content, a series of sheep dung samples were collected concurrently while observing the angle of accumulation. An accurate determination of five distinct moisture content classes for the angle of repose test was achieved using the drying technique. The collected data revealed moisture contents of 30.66%, 38.29%, 45.93%, 52.33%, and 58.63% in sequential order. Figure 3 graphically represents these five moisture content gradients of sheep dung.



Figure 2. Sheep manure after air drying.

					
Moisture content	30.66%	38.29%	45.93%	52.33%	58.63%
Densities	0.30 g/cm ³	0.41 g/cm ³	0.46 g/cm ³	0.55 g/cm ³	0.60 g/cm ³

Figure 3. Comparative analysis of sheep manure samples under different moisture content conditions.

An additional 100 unprocessed sheep excrement samples were collected and deposited into a receptacle. The particle size distribution of these samples was examined using electronic digital vernier calipers. Comprehensive statistics on the distribution of particle sizes are presented in Table 1, while the measurement procedure is illustrated in Figure 4.

Table 1. Size distribution of sheep manure particles.

Particle Size (d/mm)	Percentage Distribution (%)
[7, 10]	31%
[10, 13]	48%
(13, 16]	21%

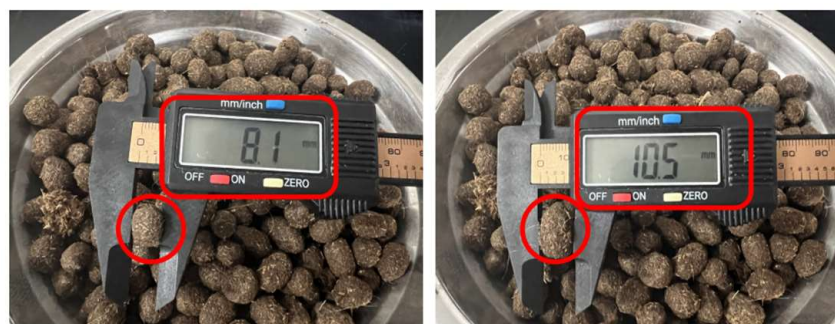


Figure 4. Measurement of sheep manure particle sizes.

2.2. Sheep Manure Stacking Angle Test and Moisture Content–Stacking Angle Model Construction

2.2.1. Sheep Manure Stacking Angle Test Device

The present study used the cylinder-lifting technique to quantify the stacking angle of samples of sheep dung. A moisture content–stacking angle model for sheep dung was developed by integrating this raw data with the moisture content of the relevant samples [37]. The prototype test arrangement, seen in Figure 5, comprises a flag-raising wheel, L-shaped bracket, stationary bar, pulley, hollow cylinder, and reception plate. The

height-to-diameter ratio of the interior material in the hollow cylinder is 3:1 [43]. The cylindrical object is hollow, measuring 50 mm in diameter and 200 mm in height, and filled with material at a depth of 75%. To ensure reproducibility, several factors related to the testing device that could potentially influence the results were carefully controlled. First, the smoothness and material consistency of the cylinder's interior surface were maintained, as variations in these factors could affect friction and thereby impact the stacking angle. Additionally, the movement precision of the flag-raising wheel was regularly verified to prevent any inconsistencies in the cylinder's lifting speed, which could alter the material's settling behavior. Furthermore, minor deviations in the setup, such as pulley friction or misalignment of the L-shaped bracket, were systematically minimized and monitored throughout the tests. These precautions were crucial to enhancing the reproducibility and reliability of stacking angle measurements across multiple trials.

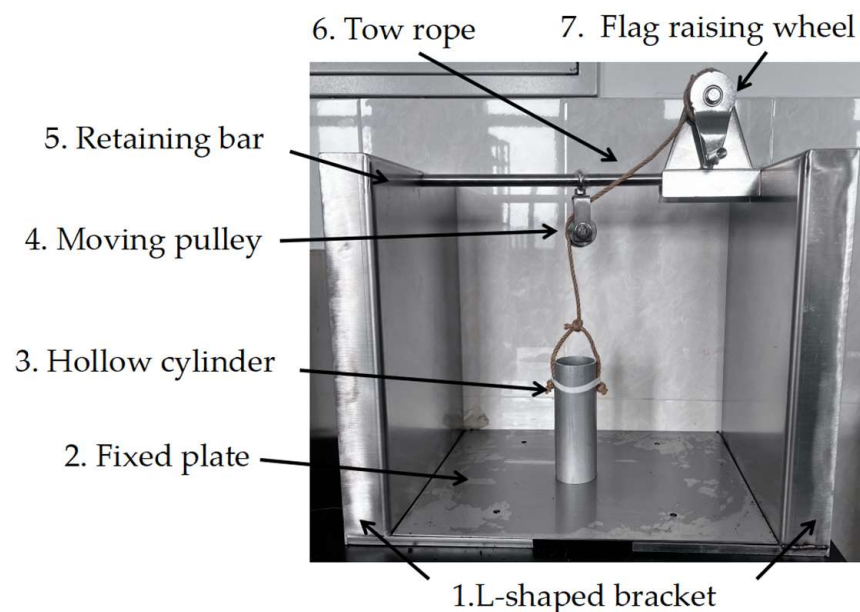


Figure 5. Cylinder lifting resting angle tester.

2.2.2. Measurement of the Angle of Accumulation of Sheep Manure

This test utilized hollow cylinders and splice plates made from 304 stainless steel. The cylindrical structure was installed vertically on the testing platform. Before commencing the assay, 3 kg of sheep excrement was introduced into the hollow cylinder. During the experiment, the flag hoisting wheel was systematically turned at a consistent velocity, which caused the hollow cylinder to ascend vertically at a steady rate of 30 mm/s. This mechanism facilitated the uniform flow of manure from the bottom of the cylinder, resulting in the formation of a natural fertilizer pile on the receiving plate. The measurement of the angle of repose was conducted in accordance with the People's Republic of China industry standard JB/T 9014.1-9014.9-1999. This standard specifically applies to the measurement of the angle of repose for granular or small bulk materials. The angle of repose is determined by calculating the tangent of the ratio between the height and the radius of the base of the conical pile. To ensure accuracy, multiple measurements were performed and averaged [43]. Measurements were obtained from four distinct orientations of the manure pile using a digital inclinometer, as shown in Figure 6. The stacking angle was determined using a consistent methodology across all five sheep dung samples, each with varying moisture content levels. To enhance the reliability of the data, each test was conducted five times for every moisture content condition. Subsequently, the average angle of accumulation for each group was calculated to ensure more accurate results.

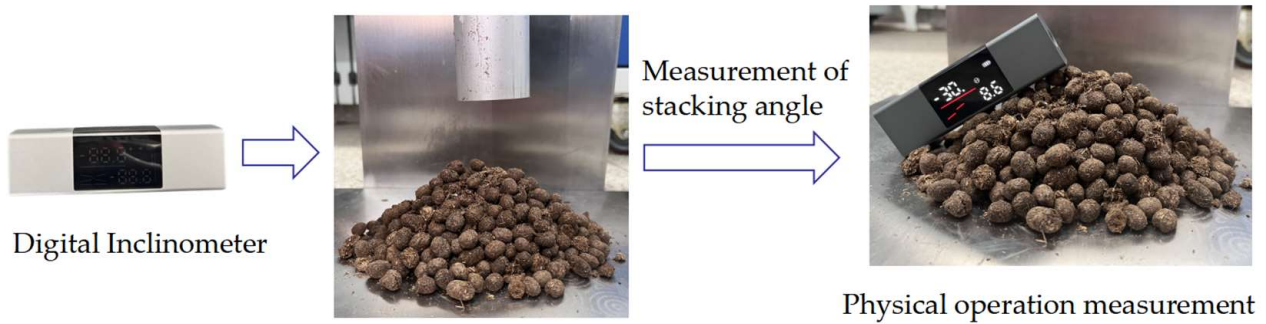


Figure 6. Stacking angle measurement.

To obtain a more precise measurement of the pile angle, a high-definition video camera was used to capture frontal photographs of the sheep dung pile. The photographs were processed with MATLAB R2022a, involving grayscale conversion, binarization, and the extraction of boundary contours and fit lines. To ensure accuracy, this process was repeated five times. The compost angle was determined by analyzing each side of the pile. MATLAB software was then used to integrate the digital inclinometer readings, compute the angles, and calculate the average of the collected compost angle data. Figure 7 illustrates how the MATLAB program quantifies the compost angle from a photograph.

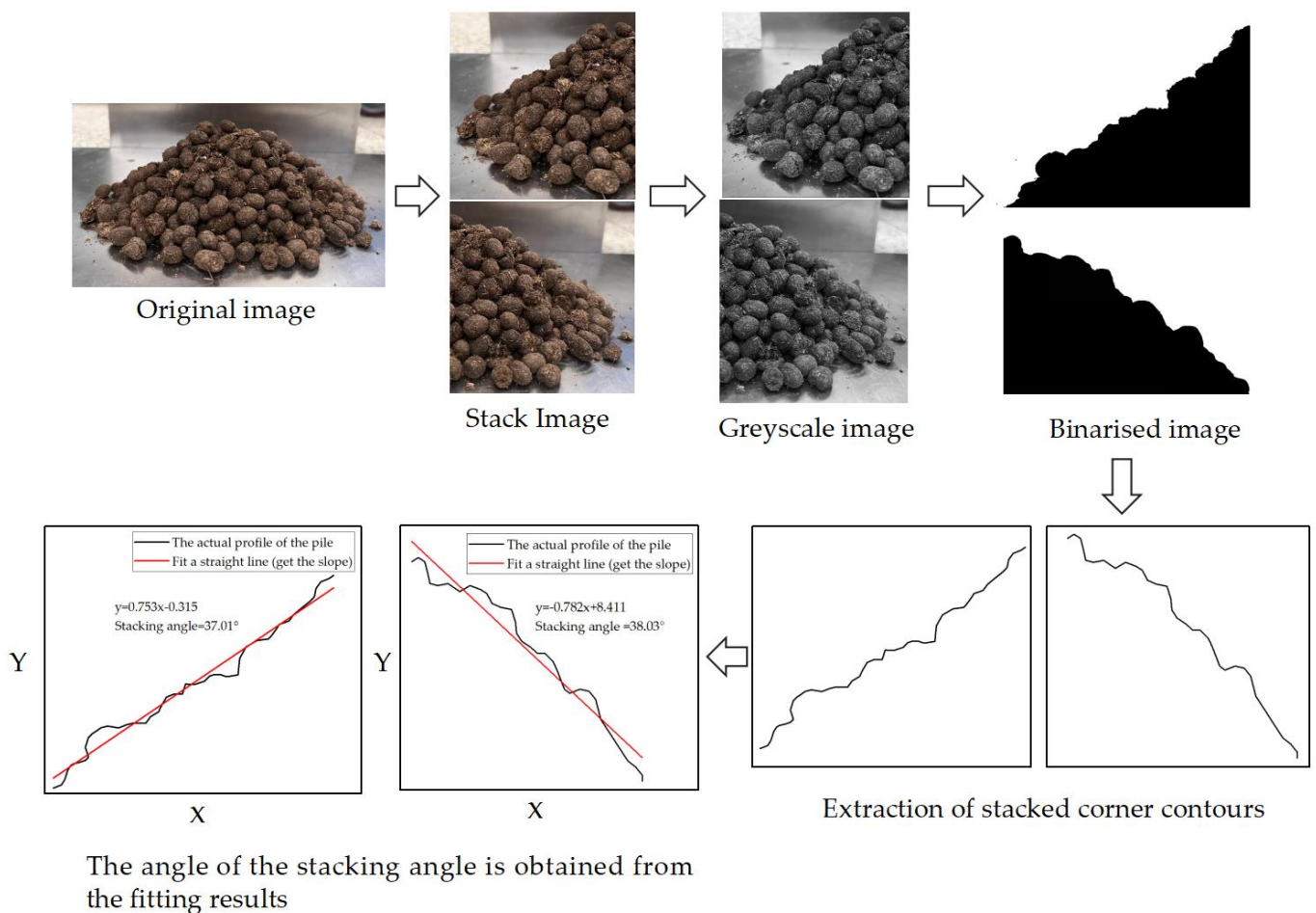


Figure 7. Measurement of stacking angle using Matlab.

A model for the water content of unrotted sheep dung and the angle of accumulation was constructed based on the results, and its connection was examined.

2.3. Discrete Meta-Modeling of Sheep Manure

2.3.1. Selection of Contact Models

Undecomposed sheep manure exhibits poor flowability and strong adhesion between particles, making the Hertz Mindlin with JKR model (referred to as the JKR model) a suitable choice for simulation. This contact model, integrated into the EDEM software, effectively captures particle adhesion. It is based on the Johnson–Kendall–Roberts (JKR) theory, which extends the Hertz–Mindlin contact model by accounting for van der Waals forces in the contact area. The JKR model is particularly suited for simulating dry powdery materials or moist particles and characterizes particle adhesion through surface energy values. This allows for a more accurate simulation of undecomposed sheep manure.

2.3.2. Setting the Simulated Particle Size

Derived from the sheep dung particle size distribution data shown in Table 1, the morphological properties of the sheep manure particles were also taken into account. In order to maintain a comparatively simple and functional simulation model, spherical particles were used to represent sheep dung particles in the EDEM simulation. Three distinct particle sizes were established in the model to correspond to the varied particle size distributions seen in Figure 8.

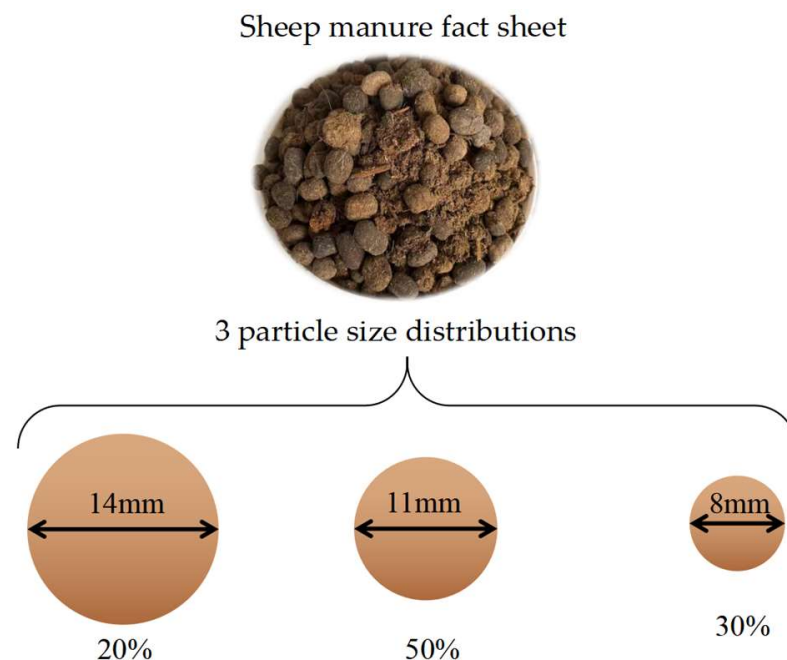


Figure 8. Model of sheep manure particles.

2.3.3. Selection of Discrete Element Simulation Parameters

Before proceeding with the next Plackett–Burman design (PBD) test, steepest ascent test, or other experimental procedures, it is crucial to accurately code the test variables. A thorough review of the relevant literature was conducted to identify the inherent physical characteristics, contact parameters, and model parameters of sheep manure materials based on the JKR (Johnson–Kendall–Roberts) theory [37–43]. Table 2 provides a detailed summary of the fundamental physical characteristics of both sheep dung and steel. By integrating data from EDEM’s General Particulate Materials Database (GEMM), the contact parameters and JKR model parameters were determined and categorized within their respective relevance ranges. These ranges are derived from the physical properties of sheep dung and steel, alongside accepted values from the literature. The exact values and ranges for these parameters are listed in Table 3.

Table 2. Sheep manure and steel base property parameters.

Materials	Density/(g·cm ^{−3})	Poisson's Ratio	Shear Modulus/MPa
Sheep manure	0.30~0.60 ^a	0.1~0.5 ^b	1.00~10.00 ^b
Steels	7.85 ^b	0.30 ^b	7.90×10^4 ^b

Note: The symbol “a” indicates that the data were obtained by experimental measurements; the symbol “b” indicates that the data were derived from published academic literature.

Table 3. Contact parameters and JKR model parameter range of sheep manure and steel material.

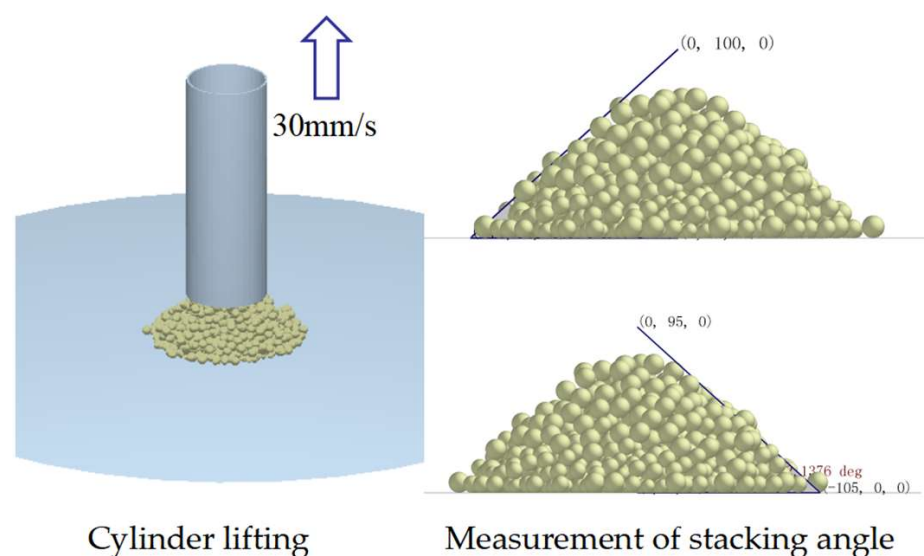
Parametric	Numerical Range
Interparticle coefficient of recovery for cow manure	0.20~0.60
Static friction factor between particles of cow manure	0.20~1.00
Rolling friction factor between cow manure particles	0.20~0.60
Coefficient of recovery of steel from cow dung	0.10~0.80
Static friction factor of cow manure steel	0.20~0.80
Rolling friction factor of cow manure steel	0.20~1.00
JKR surface energy/(J·m ^{−2})	0~0.20

2.4. Calibration of Discrete Element Parameters and Construction of Angle of Accumulation–Discrete Element Parameter Model for Sheep Manure

2.4.1. Simulated Angle of Repose for Measurement

The simulation experiments were specifically designed to ensure consistency with the actual physical tests [45]. In this phase of the study, the cylinder's lifting speed was set to 30 mm/s, producing sheep dung particles with a maximum mass of 3 kg at a rate of 0.5 kg/s. The simulation was configured with a fixed time step set to 25% of the Rayleigh time step. Data were recorded at 0.1 s intervals using a grid size of 3 mm for a total simulation duration of 10 s.

To accurately measure the stacking angles, the Protractor tool from the software toolbox was used to calculate and average the four slopes of the stack. Three prominent points from the sheep dung pile were selected as reference points for measuring the stacking angle. The angle formed by the line connecting these three points was analyzed to determine the simulated stacking angle of the sheep dung mound. Figure 9 illustrates the simulation model along with the measured stacking angle.

**Figure 9.** Simulation of cylinder lifting method.

2.4.2. Angle of Accumulation of Sheep Manure–Discrete Element Parameter Modeling

A Plackett–Burman design (PBD) experiment was developed using Design-Expert software to examine the effect of various factors on the compliance angle of sheep manure. The experiment considered 10 variables, including the density, Poisson's ratio, and shear modulus of sheep manure (as outlined in Table 2), as well as the contact parameters and JKR model parameters (as specified in Table 3). Each parameter was tested at three levels: high, medium, and low, represented by the codes 1, 0, and -1 , respectively. Table 4 provides a detailed summary of the parameter levels and coding configurations.

Table 4. Factors and levels of Plackett–Burman test.

Parametric	Encodings		
	-1	0	1
(A) Density of sheep manure/(g·cm ⁻³)	0.30	0.45	0.60
(B) Poisson's ratio in sheep manure	0.10	0.30	0.50
(C) Shear modulus of sheep manure/MPa	1.00	5.50	10.00
(D) Interparticle coefficient of recovery for sheep manure	0.20	0.40	0.60
(E) Static friction factor between particles of sheep manure	0.20	0.60	1.00
(F) Rolling friction factor between sheep manure particles	0.2	0.40	0.60
(G) Coefficient of recovery of steel from sheep manure	0.20	0.50	0.80
(H) Static friction factor of sheep manure steel	0.20	0.60	1.00
(J) Rolling friction factor of sheep manure steel	0.20	0.60	1.00
(K) JKR surface energy/(J·m ⁻²)	0	0.10	0.20

A hill-climbing test was conducted to narrow the range of relevant parameter values and establish the optimal interval. Parameters that were not statistically significant were set to their intermediate values throughout the test. Significant parameters were systematically adjusted based on a predetermined step length. The parameter set that resulted in the lowest relative error (40.66°) between the simulated stacking angle and the physical test stacking angle of sheep dung at an intermediate moisture content (45.93%) was selected as the critical value for determining the ideal range of significant parameters. For a detailed account of the hill-climbing test program and its results, refer to Section 3.

Next, a Box–Behnken test was designed based on the optimal intervals for the relevant parameters established by the hill-climbing procedure. The objective was to enhance the mathematical model describing the correlation between the stacking angle and the significant parameters. To reduce experimental bias, three central points were included to estimate error, and 15 test groups were selected, with each group repeated three times to ensure data precision. The stacking angles obtained from the tests were averaged to minimize the impact of random errors. Significant parameters were assigned values of high (+1), medium (0), and low (-1), while non-significant parameters were kept at their original levels, as in the hill-climbing test. The complete test program and corresponding results are available in Section 3.

Using the physical test stacking angles of sheep dung at five different moisture levels as targets, the optimal combination of discrete parameters was determined by solving the stacking angle–discrete parameter model developed from the Box–Behnken test. EDEM simulations were then conducted using this optimal parameter combination, with non-significant parameters set similarly to those in the hill-climbing test, to quantify the stacking angles of the manure. This study aimed to validate the accuracy of the stacking angle–discrete parameter model by comparing the simulated stacking angles with those obtained from physical testing [43].

2.5. Sheep Manure Moisture Content–Discrete Element Parameter Modeling and Engineering Validation Test

The discrete element parameters can be inferred from the stacking angle–discrete element parameter model. However, directly quantifying the stacking angle of unrotted sheep dung can lead to significant inaccuracies and is a labor-intensive task. In contrast, measuring water content is highly precise and straightforward. Therefore, a water content–discrete element parameter model was developed by correlating the water content of sheep dung with the stacking angle and integrating it with the stacking angle–discrete element parameter model. This combined model provides a flexible, practical, and highly accurate method for calibrating discrete element parameters.

The engineering validation of the discrete element parameter model for moisture content was carried out using two methods: the extraction board method and the funnel method, both of which employed the cylinder lifting approach. The simulated process was designed to match the actual operation closely, ensuring the test's accuracy. Figures 10 and 11 display the custom-made devices used for the extraction board and funnel methods.

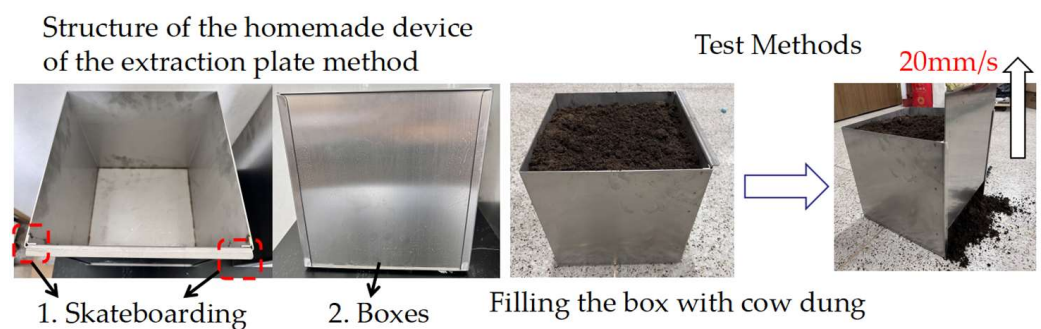


Figure 10. Self-contained device and test method for the extraction plate method.

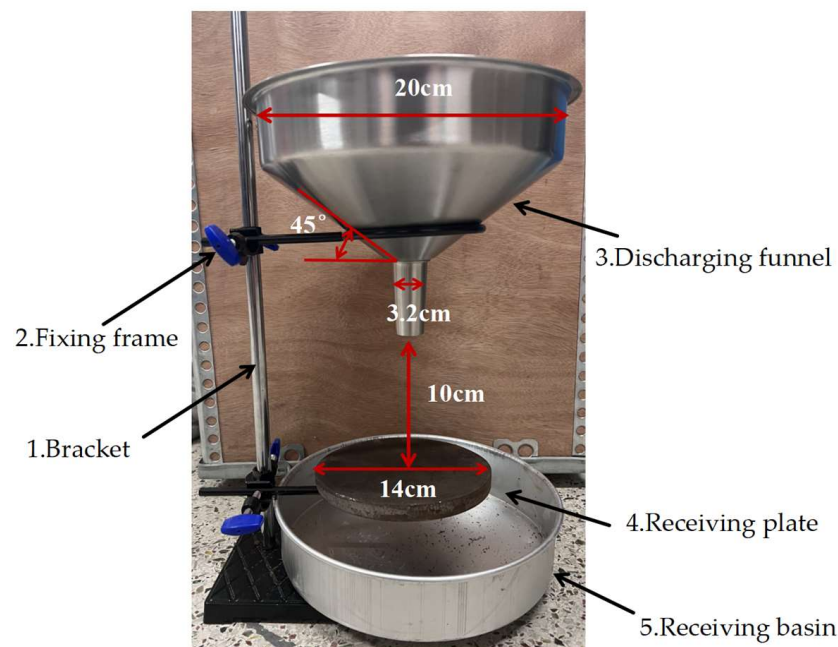


Figure 11. Homemade test apparatus for the funnel method.

Sheep manure samples with five different moisture contents, ranging from 30.66% to 58.63%, were randomly selected and evaluated for their stacking angle using both the draw plate and funnel methods. The optimal combinations of discrete parameters were determined for three specific moisture levels based on the moisture content–discrete parameter model. The corresponding stacking angles were then obtained through simulations using these optimal parameter combinations. To validate the accuracy of the moisture

content–discrete parameter model for sheep manure, the stacking angles obtained from physical experiments were compared with those derived from simulation experiments.

Each test series was repeated five times to ensure consistency and reliability. The results across these repetitions exhibited minimal variation, with standard deviations calculated for each set of stacking angles. These deviations consistently fell within an acceptable range, confirming the experiment’s repeatability. Any outliers identified during the trials were re-tested to ensure the integrity of the data. The average values from the repeated tests were subsequently used to compare the stacking angles from physical and simulation experiments, thereby further validating the model’s precision and robustness.

3. Results

3.1. Water Content–Stacking Angle Modeling

Table 5 presents the angle of accumulation of unrotted sheep manure samples with varying moisture levels as determined by physical testing.

Table 5. Stacking angle of cow manure with different moisture content.

Moisture content/%	30.66	38.29	45.93	52.33	58.63
Stacking angle/(°)	36.36	38.12	40.66	42.63	45.63
Standard deviation of stacking angle/(°)	0.58	0.36	0.21	0.46	0.67

With the application of Origin software, polynomial and linear fits were performed to analyze the correlation between the water content of sheep dung samples and their stacking angle, based on the data shown in Table 5. The water content–stacking angle models obtained are illustrated in Equations (2) and (3). The graph depicting the correlation between water content and stacking angle of sheep dung may be seen in Figure 12.

$$y = 0.323x + 25.884 \quad (R^2 = 0.984) \quad (2)$$

$$y = 0.00001x^3 + 0.002x^2 + 0.087x + 31.678 \quad (R^2 = 0.997) \quad (3)$$

where y is the angle of accumulation of sheep manure, (°); x is the moisture content of sheep manure %.

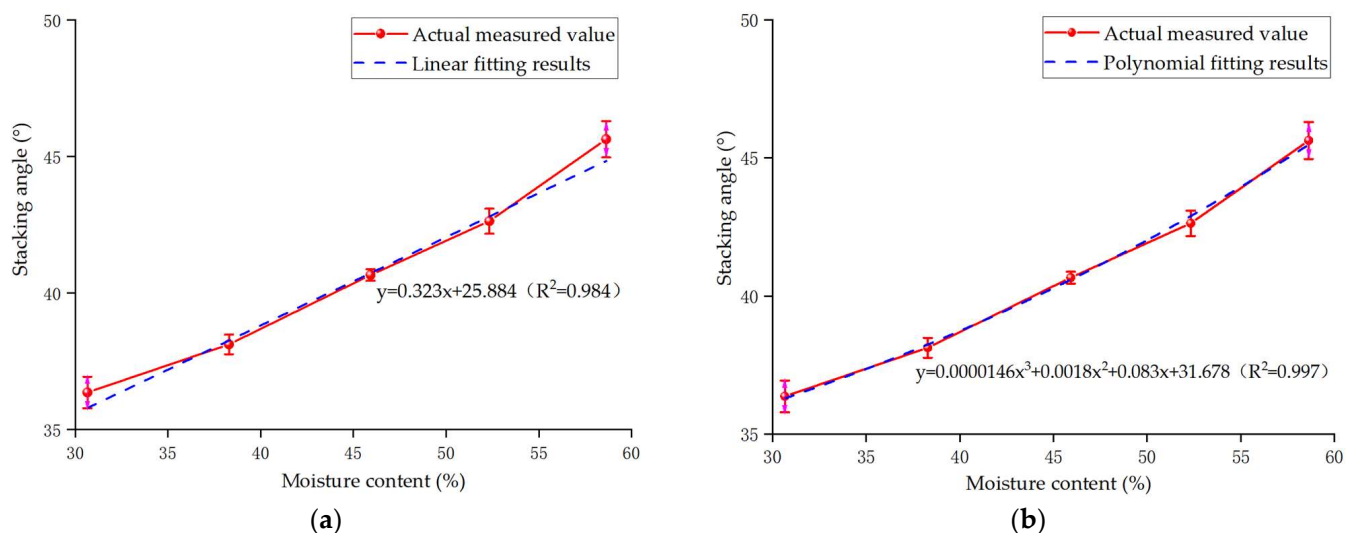


Figure 12. Curve of moisture content of ssheep manure versus stacking angle. (a) Linear fitting results; (b) Polynomial fitting results.

Empirical analysis of Equations (2) and (3) demonstrated that the polynomial model, Equation (3), provided a significantly better fit compared to the linear model, Equation (2). This indicates that the polynomial model captures the non-linear relationship between moisture content and the stacking angle of sheep manure more effectively. The non-linear effects observed in this context may be attributed to the complex interactions between moisture content and the physical properties of sheep manure, such as cohesion and friction. As moisture increases, these properties may not change in a strictly proportional manner, leading to a non-linear response in the stacking angle. Therefore, using the polynomial model, Equation (3), in conjunction with moisture content measurements, allows for a more accurate estimation of the stacking angle.

An analysis of the rheological properties of sheep dung as a granular material revealed a strong positive correlation between the stacking angle and moisture content. The stacking angle consistently increased as moisture content rose within the range of 30.66% to 58.63%. This phenomenon is primarily attributed to changes in the contact forces between the particles. Specifically, the presence of moisture significantly enhanced the adhesive forces among the sheep dung particles, promoting particle aggregation. As moisture content increased, the improved bonding between particles reduced the flowability of the manure, reflected by the increase in stacking angle. Additionally, higher moisture levels may influence the coefficient of friction between particles. Increased moisture could lead to the formation of a concentrated water film on the pellet surfaces, indirectly raising friction between particles and slowing down their movement. Furthermore, moisture may cause particle swelling and increase deformation between particles, contributing to the higher stacking angles observed. In summary, the effect of moisture content on the stacking angle of sheep dung is not limited to enhanced adhesion between particles but also impacts the rheological properties by increasing friction and altering particle structure.

3.2. Significance Parameter Screening Results and Analyses

A Plackett–Burman Design was undertaken utilizing Design-Expert 13.0 software. The precise experimental procedure and its related outcomes are shown in Table 6, where factors A to J correspond to the coding of each effect factor.

Table 6. Scheme and results of Plackett–Burman test.

Test No.	Considerations										Stacking Angle (°)
	A	B	C	D	E	F	G	H	I	J	
1	1	−1	1	−1	1	1	1	−1	−1	−1	84.32
2	1	−1	1	1	−1	−1	−1	1	−1	1	32.65
3	1	1	1	−1	−1	1	−1	1	1	−1	10.36
4	−1	1	1	−1	−1	−1	1	−1	1	1	49.65
5	−1	−1	−1	−1	1	1	−1	1	1	1	41.48
6	1	1	−1	−1	1	−1	1	1	−1	1	27.93
7	−1	−1	1	1	1	−1	1	1	1	−1	28.49
8	1	1	−1	1	1	−1	−1	−1	1	−1	40.33
9	−1	1	1	1	1	1	1	1	−1	−1	27.98
10	−1	−1	−1	−1	−1	−1	−1	−1	−1	−1	79.81
11	−1	1	−1	1	−1	1	1	1	−1	−1	62.73
12	1	−1	−1	1	−1	1	1	−1	1	1	36.82

A significance analysis of the Plackett–Burman Design (PBD) test findings was conducted using the data from Table 6 loaded into Design-Expert software, as shown in Table 7. The p -value of 0.0462 ($p < 0.05$) of the model suggests statistical significance, therefore verifying the reliability of the estimate.

Table 7. Significance analysis of Plackett–Burman test results.

Source of Variance	Effect (Scientific Phenomenon)	Mean Square and	<i>p</i>	Significance Number
A	−1.07	13.80	0.2260	8
B	−1.07	13.72	0.2266	9
C	−1.10	14.45	0.2212	7
D	1.79	38.27	0.1394	6
E	9.19	1012.92	0.0275 *	3
F	11.98	1721.53	0.0211 *	2
G	−3.84	176.56	0.0657	4
H	1.05	13.29	0.2299	10
I	1.94	45.36	0.1284	5
J	13.92	2323.81	0.0182 *	1

Note: The symbol “*” indicates a statistically significant difference ($p < 0.05$). The same applies in the subsequent sections.

The experimental results in Table 7 demonstrate that the coefficient of static friction (E), the coefficient of rolling friction between particles (F), and the surface energy of JKR (J) significantly influenced the stacking angle in the sheep manure simulation ($p < 0.05$). The positive effects of these three factors on the stacking angle can be explained as follows.

An increase in the JKR surface energy of sheep dung particles led to stronger adhesion between particles, thereby reducing the overall fluidity of the manure. This decrease in mobility directly affects the stacking behavior of sheep manure. As a result, a rise in JKR surface energy is expected to increase the simulated stacking angle. The rolling friction coefficient and static friction coefficient between particles are key determinants of particle mobility. As these friction coefficients increase, particles encounter greater resistance to rolling and sliding, reducing their mobility and leading to a higher stacking angle. Since the model involves four distinct sizes of spherical particles, particle motion is primarily characterized by rolling. Therefore, the rolling friction coefficient has a more significant impact on the stacking angle than the static friction coefficient.

To streamline subsequent tests, including the steepest climb test, Box–Behnken design test, and validation test, only the three most critical factors were considered. This approach simplifies the experimental design while ensuring the accuracy and consistency of the results obtained [42].

3.3. Determination of Optimal Intervals for Discrete Element Parameters

The design and results of the hardest climb test are shown in Table 8. The calculation of the relative error (N , %) was performed using Equation (4).

$$N = \frac{|\sigma - \theta|}{\theta} \times 100\% \quad (4)$$

where σ is the simulation test stacking angle, (°).

Table 8. Hill-climbing test program and results.

Test No.	Considerations			Simulated Stacking Angle/ (°)	Relative Error/ %
	JKR Surface Energy/(J·m ^{−2})	Rolling Friction Factor between Sheep Manure Particles	Static Friction Factor between Particles of Sheep Manure		
1	0	0.20	0.20	25.32	37.73
2	0.05	0.30	0.40	37.69	7.30
3	0.10	0.40	0.60	50.36	23.86
4	0.15	0.50	0.80	56.12	38.02
5	0.20	0.60	1.00	63.29	55.66

An analysis of the climb test data clearly shows that test number 2 exhibits the lowest relative inaccuracy of 7.30% in comparison to the stacking angle of the physical test. The aforementioned collection of parameters signifies the intermediate level value that falls within the ideal intervals of the important parameters. More precisely, the ideal intervals are 0.00–0.10, 0.20–0.40, and 0.20–0.60, taken in that order.

3.4. Stacking Angle–Discrete Element Parameter Modeling

The coding and corresponding values for each significant parameter setting are shown in Table 9. The Box–Behnken experimental design and its results are detailed in Table 10. The ANOVA results of the experimental model are provided in Table 11.

Table 9. Box–Behnken parameter level coding table.

Level	(E) Interparticle Static Friction Factor	(F) Inter-Particle Rolling Friction Factor	(J) JKR Surface Energy/ (J·m ^{−2})
−1	0.20	0.20	0
0	0.40	0.30	0.05
+1	0.60	0.40	0.10

Table 10. Box–Behnken test program and results.

Test No.	Considerations			Simulated Stacking Angle/(°)
	E	F	J	
1	−1	0	1	48.36
2	0	0	0	33.69
3	0	1	1	55.66
4	0	1	−1	36.66
5	−1	1	0	53.36
6	1	−1	0	56.13
7	0	0	0	36.14
8	0	−1	−1	23.60
9	0	0	0	37.15
10	0	−1	−1	23.68
11	1	0	−1	36.63
12	−1	−1	0	34.12
13	1	0	1	54.77
14	1	1	0	60.12
15	−1	0	−1	21.03

Table 11. Box–Behnken experimental model ANOVA.

Source of Variance	Mean Square and	Degrees of Freedom	Mean Square	<i>p</i>
Modeling	2370.04	9	263.34	<0.0001 **
E	322.33	1	322.33	0.0001 **
F	167.84	1	167.84	0.0005**
J	681.87	1	681.87	<0.0001 **
EF	58.14	1	58.14	0.0057 **
EJ	21.11	1	21.11	0.0386 *
FJ	3.11	1	3.11	0.3337
E ²	160.95	1	160.95	0.0006 **
F ²	199.59	1	199.59	0.0004 **
J ²	22.28	4	22.28	0.0353 *
Residual	13.60	5	2.72	
Lost proposal	7.26	3	3.63	0.3180
Pure error	6.33	2	2.11	
Aggregate	2383.63	14		

Note: The symbol “*” indicates a statistically significant difference ($p < 0.05$), while the symbol “**” indicates a highly significant statistical difference ($p < 0.01$). The same applies in the subsequent sections.

The experimental data were processed using Design-Expert 13.0 software to obtain the second-order regression equation for the stacking angle:

$$y = 35.66 + 6.35E + 5.47F + 11.03J - 3.81EF - 2.3EJ - 1.2FJ + 7.23E^2 + 8.05F^2 - 2.69J^2 \quad (5)$$

where (E) represents the static friction factor between sheep manure particles, (F) represents the rolling friction factor between sheep manure particles, and (J) represents the JKR surface energy in (J/m²). The results of the ANOVA for the model are shown in Table 11. The primary terms (E), (F), and (J) significantly affect the angle of accumulation of sheep manure. Similarly, the secondary terms (E²) and (F²) also have significant effects. The interaction terms (EF) and (EJ) are extremely significant, while the interaction term (FJ) is significant. Additionally, the secondary term (J²) significantly impacts the angle of accumulation of sheep manure particles. These results indicate that the relationship between the factors and the response values is not simply linear, with the degree of influence ranked as (J > E > F), i.e., JKR surface energy > interparticle static friction factor > interparticle rolling friction factor.

An analysis of the constructed regression model shows that ($p < 0.0001$), proving a highly significant association between the dependent variable and all independent variables. The p value for the misfit term is 0.3180, indicating that the regression equations fit well with the measured data. The coefficient of determination (R^2) is 0.9943, and the adjusted coefficient of determination (R_{adj}^2) is 0.9840, both close to 1. These indicators demonstrate that the regression equation is highly reliable, with a model precision indicator of 28.537, proving its high accuracy.

Further processing of the regression analysis model, balancing the need to ensure overall significance against the statistical insignificance of the out-of-fit term, revealed that excluding the factor (FJ) enhanced the predictive accuracy of the model. This improvement resulted in the refined regression Equation (6).

$$y = 35.66 + 6.35E + 5.84F + 10.76J - 3.81EF - 2.3EJ + 7.6E^2 + 7.68F^2 - 3.06J^2 \quad (6)$$

After eliminating the factor with an insignificant effect (FJ), the response surface analysis of the interaction of the respective variables (EF, EJ) on the angle of accumulation of sheep manure was performed based on the regression equation, as shown in Figure 12. The analysis of variance of the improved regression model is presented in Table 12. The improved coefficient of determination ($R^2 = 0.993$) and the adjusted coefficient of determination ($R_{adj}^2 = 0.984$) were both close to 1, indicating a good model fit. The precision improved to 29.798 from the pre-improvement period, and the model's credibility was further increased for predicting the angle of accumulation of sheep manure pellets.

Table 12. Box–Behnken test of the optimization model ANOVA.

Source of Variance	Mean Square and	Degrees of Freedom	Mean Square	p
Modeling	2366.92	8	106.24	<0.0001 **
E	322.33	1	115.75	<0.0001 **
F	253.74	1	91.12	<0.0001 **
J	752.18	1	270.10	<0.0001 **
EF	58.14	1	20.88	0.0038 **
EJ	21.11	1	7.58	0.0331 *
E ²	205.72	1	73.87	0.0001 **
F ²	210.14	1	75.46	0.0001 **
J ²	33.35	4	11.98	0.0135 *
Residual	16.71	5		
Lost proposal	10.37	3	1.64	0.3476
Pure error	6.33	2		
Aggregate	2383.63	14		

Note: The symbol “*” indicates a statistically significant difference ($p < 0.05$), while the symbol “**” indicates a highly significant statistical difference ($p < 0.01$). The same applies in the subsequent sections.

According to Figure 13, under a constant rolling friction factor between sheep manure particles, the simulated stacking angle increases with the elevation of the static friction factor. Conversely, when the static friction factor is constant, the stacking angle also rises with an increase in the rolling friction factor. Additionally, the simulated stacking angle decreases and then increases when both static and rolling friction factors are increased simultaneously. Increasing the JKR surface energy results in an increase in the simulated stacking angle with a constant static friction factor. Compared to the static friction factor, increasing the JKR surface energy is more effective in raising the stacking angle. When the JKR surface energy and static friction factor are increased simultaneously, the stacking angle shows a tendency to decrease and then increase.

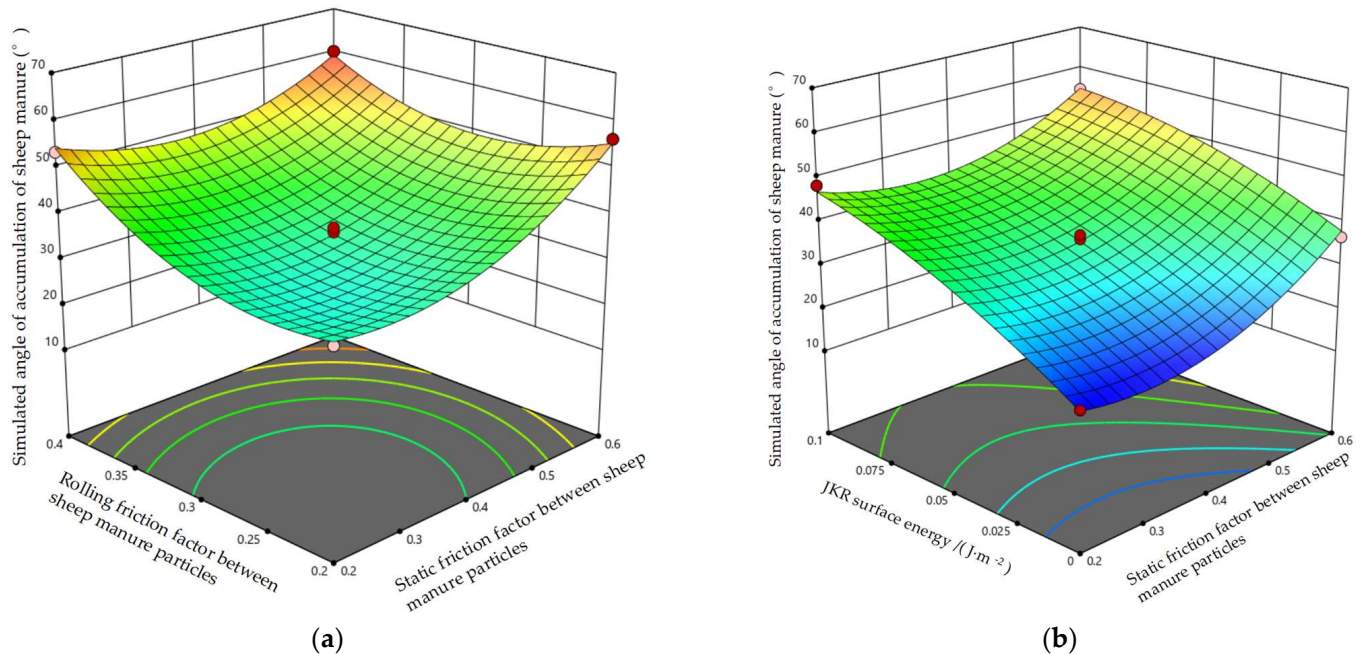


Figure 13. Response surface of interaction factors on simulated stacking angle of sheep manure. (a) Interaction effects of EF; (b) Interaction effects of EJ.

3.5. Stacking Angle–Discrete Element Parametric Model Validation

According to Equation (6), the required set of discrete element model parameters was determined directly from the physical tests carried out on sheep manure samples with different water content. Using Design-Expert 13 software, an optimal solution was obtained by performing an objective value-seeking process. This optimal solution included the discrete element model parameters: JKR surface energy, rolling friction factor between sheep manure particles, and static friction factor between sheep manure particles. The optimal values of these parameters and the corresponding validation test results for sheep manure under different moisture content conditions are shown in Table 13.

Table 13. Parameter optimization of discrete meta-model for cow manure under different water content conditions and its validation.

Moisture Content/ %	Static friction Factor between Particles of Sheep Manure	Rolling Friction Factor between Sheep Manure Particles	JKR Surface Energy/ (J·m ⁻²)	Simulated Stacking Angle/ (°)	Relative Error/ %
30.66	0.39	0.24	0.03	36.11	0.69
38.29	0.51	0.38	0.01	37.22	2.36
45.93	0.58	0.24	0.04	41.23	1.40
52.33	0.59	0.36	0.05	44.01	3.24
58.63	0.59	0.37	0.09	47.21	3.46

The results of the stacking angle of sheep manure samples at 45.93% moisture content for the simulated versus the actual physical tests are presented in Figure 14. Based on the data analysis in Table 13, the optimal combination of the three key parameters was obtained after determining the discrete element model parameters for the stacking angle. This combination ensured that the relative error between the simulated and experimentally measured stacking angles of sheep manure samples was maintained below 3.46% at different moisture content levels. This demonstrates the reliability of the developed model for discrete element parameter determination.

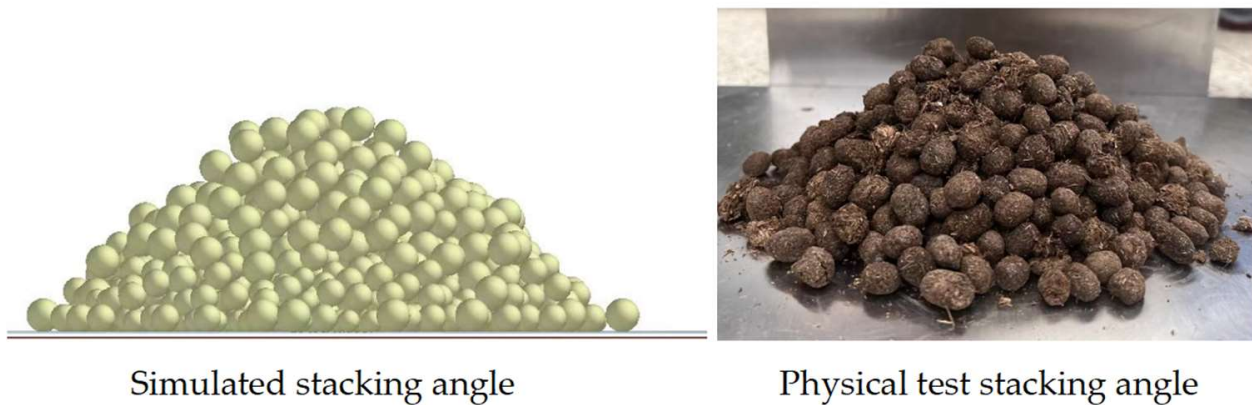


Figure 14. Response surface of interaction factors on simulated stacking angle of sheep manure.

3.6. Water Content–Discrete Element Parameter Model Construction and Validation

To accurately and quickly calibrate the discrete element parameters, models were derived to relate the moisture content to these parameters, specifically the coefficient of static friction between sheep manure particles, the coefficient of rolling friction between sheep manure particles, and the JKR surface energy. These models were derived from Equations (3) and (6), resulting in a combined model for water content and discrete element parameters, as shown in Equation (7). This derivation integrates the water content–stacking angle model with the stacking angle–discrete element parameter model for sheep manure.

$$0.00001x^3 + 0.002x^2 + 0.087x + 31.678 = 35.66 + 6.35E + 5.84F + 10.76J - 3.81EF - 2.3EJ + 7.6E^2 + 7.68F^2 - 3.06J^2 \quad (7)$$

Based on the sheep manure moisture content–discrete element parameter model, five sets of target values for discrete element parameter combinations at random moisture content were generated using Design-Expert 13.0 software. The angle of accumulation of sheep manure was determined through physical and simulation tests using the pull-board and funnel methods. To ensure data reliability, each test setup was replicated five times, and the average value was taken as the final result. The measured data are presented in Tables 14 and 15.

Table 14. Results of validation tests of the pumped plate method.

Moisture Content/ %	Static Friction Factor between Particles of Sheep Manure	Rolling Friction Factor between Sheep Manure Particles	JKR Surface Energy/ (J·m ^{−2})	Simulated Stacking Angle/ (°)	Relative Error/ %
32.66	0.52	0.29	0.01	36.69	0.87
36.37	0.30	0.33	0.05	37.54	1.84
43.36	0.44	0.35	0.02	39.29	2.09
51.36	0.59	0.22	0.05	41.56	1.83
56.13	0.23	0.39	0.07	43.04	3.74

Table 15. Results of the funnel method validation test.

Moisture Content/ %	Static Friction Factor between Particles of Sheep Manure	Rolling Friction Factor between Sheep Manure Particles	JKR Surface Energy/ (J·m ⁻²)	Simulated Stacking Angle/ (°)	Relative Error/ %
32.66	0.52	0.29	0.01	36.69	4.89
36.37	0.30	0.33	0.05	37.54	1.92
43.36	0.44	0.35	0.02	39.29	1.00
51.36	0.59	0.22	0.05	41.56	2.64
56.13	0.23	0.39	0.07	43.04	1.91

Given the data in Tables 14 and 15, the relative errors between the modeled stacking angle of sheep manure and the actual measured stacking angle of sheep manure were not more than 3.74% and 4.89%, respectively. This result confirms the reliability of the established moisture content–discrete element parameter model. The results of the stacking angle of sheep manure in the simulation and physical tests at a moisture content of 37.66% are shown in Figure 15.

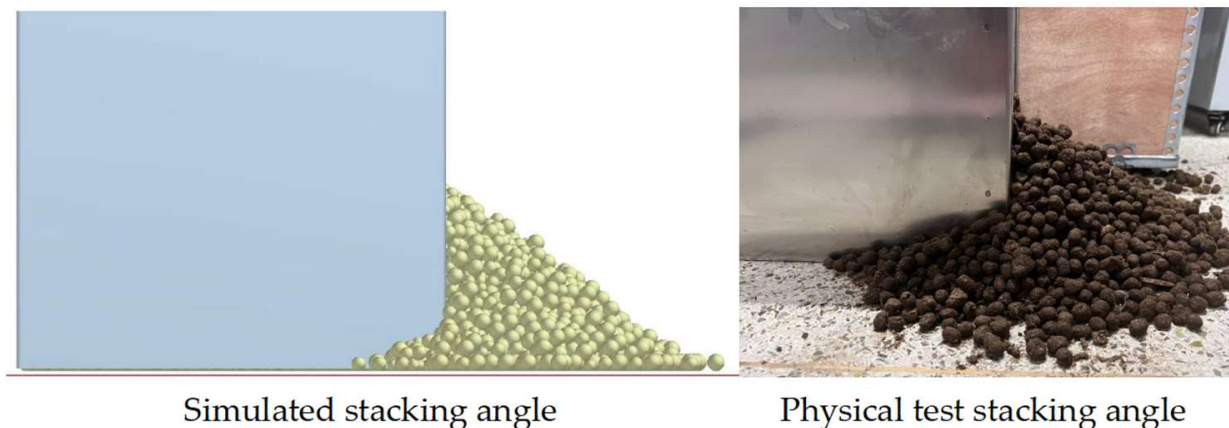


Figure 15. Simulation and physical test values for the angle of accumulation of sheep manure determined using the pumping plate method.

3.7. Parametric Modeling of Sheep Manure via Cylinder Lifting, Pumping Plate, and Funnel Methods

The sheep manure moisture content–discrete element parameter model showed a slightly higher relative error compared to the angle of accumulation–discrete element parameter model. This was primarily due to the use of the pull-board and funnel methods, which differ from the cylinder lifting method employed in this test. Despite these methodological differences, the pull-board and funnel methods provided additional validation for engineering applications and confirmed the reliability of the models. The errors measured by all three models remained within a relatively low range, demonstrating their ability to accurately predict the discrete element parameters. Through engineering practice, the constructed moisture content–discrete element parameter models proved highly reliable, with relative errors not exceeding 4.89%. All three models are effective for calibrating the discrete element parameters of sheep manure under varying moisture content conditions, highlighting their versatility in different applications.

4. Discussion

The aim of this study was to explore significant fluctuations in moisture content in fresh sheep manure, which have previously caused inconsistencies and challenges in calibrating discrete element simulation parameters. An experimental study was conducted

using stacking angle as the response variable to establish accurate simulation parameters for the composting process.

A model was developed utilizing cylindrical lifting technology to correlate moisture content with stacking angle, achieving a correlation coefficient of up to 0.997. This strong correlation indicates that the model can reliably predict the stacking angle based on moisture content, which is essential for accurate modeling of the composting process. This advancement represents a significant step toward effectively simulating the behavior of sheep manure at varying moisture levels.

Using the Hertz–Mindlin model in conjunction with JKR adhesion, three EDEM particle models were created, differentiating them by particle size characteristics to accurately reflect the particle size distribution of sheep manure. A comprehensive series of experiments—including the Plackett–Burman, steepest ascent, and Box–Behnken methods—identified JKR surface energy as one of the ten key parameters for simulations. Further refinements through the Plackett–Burman and Box–Behnken approaches enabled the determination of precise values for JKR surface energy, rolling friction coefficient, and static friction coefficient.

Subsequently, a model was developed to establish a relationship between stacking angle and discrete element parameters, achieving a p -value of less than 0.0001 and a relative error of less than 3.46%. The high accuracy of this model confirms its efficacy in predicting discrete element properties based on stacking angle.

The moisture content–discrete element parameter model was constructed by integrating the moisture content–stacking angle model with the stacking angle–discrete element parameter model. This combined model underwent verification using the draw-plate and technical funnel methods, yielding a relative error of less than 4.89%. These verification results affirm the reliability and accuracy of the model in practical applications.

Overall, the results indicate that the unique properties of sheep manure can be reliably predicted when considering moisture content, providing a robust method for estimating composting system simulation parameters. These empirical models establish a solid foundation for simulating the composting behavior of sheep manure under varying moisture conditions, thereby enhancing the accuracy and efficacy of agricultural engineering simulations.

A comparison of the research findings with calibration studies involving other types of animal manure revealed that the three discrete element parameters most significantly influencing the angle of inclination are JKR surface energy, static friction factor between particles, and rolling friction factor among manure particles. However, the ranking of these factors by degree of influence varies among studies [37–43].

Future research should focus on broadening the applicability of these models to different types of manure and enhancing methodologies to further minimize residual errors. Additionally, investigating the effects of other environmental and material factors on discrete element characteristics could improve simulation accuracy and provide a more comprehensive understanding of the composting process.

5. Conclusions

- (1) The present work effectively established a comprehensive calibration procedure for the discrete element characteristics of unrotted sheep dung. By addressing the significant fluctuations in water content that previously hindered the accurate calibration of simulation parameters for composting processes, we developed a robust water content–stacking angle model using the cylinder-lifting technique. This model achieved an impressive correlation coefficient of 0.997, providing a reliable foundation for predicting the stacking angle based on varying water content levels, thereby enhancing the feasibility and precision of composting simulations.
- (2) Development and validation of discrete element models: we created three discrete element method (DEM) particle models using the Hertz–Mindlin with JKR bonding model, incorporating the particle size distribution of sheep manure. Comprehensive

testing of JKR surface energy, including the Plackett–Burman test, the steepest ascent test, and the Box–Behnken test, identified it as one of the ten critical parameters. Further analysis confirmed JKR surface energy, rolling friction factor, and static friction factor as key parameters, leading to the development of a stacking angle–discrete element parameter model with a p -value below 0.0001 and a relative error of 3.46% or less. Validation of the comprehensive water content–discrete element parameter model, conducted using both the pumping plate and hopper methods, resulted in a relative error of 4.89% or less. These results demonstrate that the discrete element characteristics of sheep manure can be accurately predicted based on water content.

- (3) This study provides a reliable and universally applicable approach for estimating discrete element parameters in the simulation of sheep manure for composting operations. The model’s robustness and high accuracy make it a valuable tool for agricultural engineering, enabling more precise and efficient simulations. Future research should focus on further refining this model and evaluating its applicability to different types of organic waste, thus expanding its potential impact on composting and related fields. Additionally, examining the influence of other environmental and material factors could enhance the depth and accuracy of these simulations.

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