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DESIGN AND ANALYSIS OF A VERTICAL SCREW STIRRING DEVICE FOR FEEDING DAIRY GOATS

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Abstract
Aiming at the problems of low quality of milk production and low feeding efficiency caused by uneven stirring of components in total mixed ration (TMR), a vertical screw stirring device for feeding dairy goat was designed. In this study, based on the material properties of TMR for dairy goats, the pitch (S), bottom inclination angle (Z), and rotational speed of the vertical screw (n) and the sidewall angle (β) and loading rate (L) of the mixing chamber were simulated and analysed by the discrete element method, the optimal parameter combination for the system were determined. Furthermore, a testbed of the stirring device was built in accordance with simulation analysis conclusions, verifying the working performance of the device. Results demonstrated that when S = 300 mm, Z = 70°, β = 105°, n = 60 r/min, L = 70 %, the C_V of mixing uniformity is 12.95 % and mixing power is 1.35 kW. A test showed that the C_V of mixing uniformity was 13.03 %, and that of mixing power was 1.41 kW. These results are basically consistent with the simulation analysis results. The proposed results provide evidence for the design of feeding devices for dairy goats.
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Key Words: Vertical Screw, Feeding Device, Discrete Element Method, Total Mixed Ration, Mixing Uniformity

1. INTRODUCTION

Feeding is a key procedure in cultivating dairy goats. Owing to uneven stirring of components in total mixed ration (TMR), dairy goats have low quality of milk production and low feeding efficiency, thus restricting the development of the dairy goat cultivation industry. Using feeding machines with reasonable structure not only can acquire nutrition-balanced mixing fodders quickly to improve the milk quality of dairy goats but also lowers feeding cost and improves feeding efficiency [1]. As the core part of the feeding machine, the TMR stirring device influences its quality directly. Hence, designing a stirring device with reasonable structure has crucial significance to feeding machines.

Full stirring of TMR based on the screw structure is a common method used in existing feeding machines. The screw structure is mainly divided into horizontal and vertical screws. The working performance and interaction of structural parameters have attracted extensive attention. For this reason, scholars in the world have reported associated studies. Pezo et al. [2] discussed the relationship between the geometric size of screws and the diameter of stirring particles during mixed transport of zeolites and quartz through a horizontal screw mixed conveyor, This study found a direction relationship between the geometric size of screws and the diameter of stirring particles, but the influence of screw structure size on mixing uniformity was not discussed. Costa et al. [3] analysed the effects of loading capacity, mixing time and spiral speed on the mixing uniformity of the vertical double helix mixer through experiments, and concluded that loading capacity and mixing time had a great influence on the uniformity, but the single helix structure was not studied and analysed. Vegricht et al. [4] compared the mixing uniformity of TMR and oil consumption of machines with vertical and horizontal screw structures through an experiment. They found that both structures had good mixing uniformity, although the horizontal screw structure reported a higher oil consumption than the vertical screw structure. The relevant influencing factors were not discussed deeply owing to limitations in mixing uniformity and oil consumption of the two structures. Seflek and Haciseferogullari [5] focused on the stress analysis of the screw structure of an existing vertical screw mixer and determined the safety coefficient but did not discuss the interaction between screw structures and stirring particles. Wang's research team [6, 7] also tested horizontal screw TMR mixers and paddle mixers appropriate for feeding cows, thus determining the optimal combination of technological parameters for different mixer types. However, vertical screw mixers, which are the core part, were not analysed.

To sum up, scholars in the world emphasize on the qualitative analysis of factors such as mixing uniformity, mixing power, TMR particle size, loading capacity, mixing time, and screw rotational speed of existing horizontal and vertical screw stirring devices. No study exists on screw structure and the quantitative evaluation of mutual influences between the mixing uniformity of TMR for dairy goats and vertical screw structures. Moreover, the influences of screw structure parameters on fodder particle movement of multiple components have not been discussed. Simulation methods are widely used in the optimization of mechanical structures [8-10]. This study designed a small-sized vertical screw stirring device for once feeding in small-scale dairy goat farms (considering 100 goats for example). The influences of the structural parameters and working parameters of the device on the particle movement of different components in TMR for dairy goats during stirring were analysed through the discrete element method. The optimal parameters were determined. Moreover, the reasonability of the design was verified through an experiment. Research conclusions could provide references for the design of vertical screw stirring devices for feeding dairy goats.

2. MATERIAL AND METHODS

2.1 General structure and working principle

The vertical screw stirring device for feeding dairy goats can mix and stir different types of fodders, thus realizing nutritionally balanced TMR. This device can improve palatability, lower feeding cost, and save labour resources of dairy goats. The major structure is composed of a rack, a mixing chamber, a vertical screw, and a discharge gate (Fig. 1).

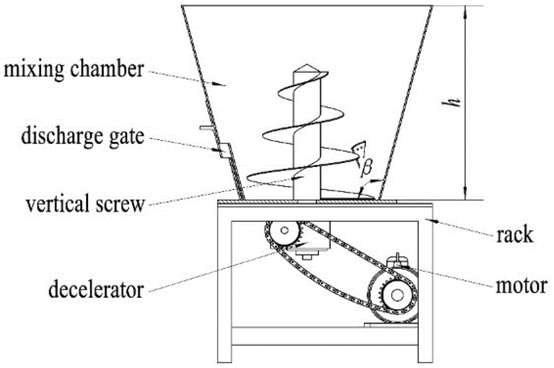


Figure 1: Structure of the designed vertical screw stirring device.

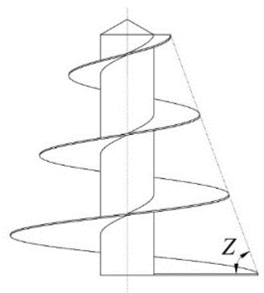


Figure 2: Vertical screw.

The motor provides power for the vertical screw stirring device. TMR for dairy goats is loaded in the mixing chamber. The vertical screw is installed vertically at the middle of the mixing chamber, with its bottom connected to the decelerator at the bottom, chain drive, and motor. While working, the motor directs the rotation of the auger through the decelerator, and TMR in the chamber is lifted up to the top upon the push force of auger blades. As a result, the top TMR is squeezed and pushed toward the tank wall, which is far away from the vertical screw. When the bottom TMR moves upward, the upper TMR moves downward along the tank wall. In this way, cyclic flipping, stirring, and rubbing of TMR in the mixing chamber are realized. After TMR is mixed uniformly, it is discharged through the discharge gate on the lower sidewall of the mixing chamber.

2.2 Theoretical design of major structural parameters

Mixing chamber: As one of the key parts of the stirring device, the mixing chamber can load materials and assist in rubbing. It usually adopts a structure with large upper end and small lower end (Fig. 1). The volume of the mixing chamber is obtained as follows:

$$V = \pi h(\frac{D}{2})^2 + \frac{h^2 D}{-\tan\beta} \tag{1}$$

where V is the volume of the mixing chamber (mm^3). h is the height of the mixing chamber (mm). D refers to the diameter at the bottom of the mixing chamber (mm). β refers to the inclination angle of the sidewall of the mixing chamber (°).

For the convenience of uniform mixing and prevention of TMR spill over, the loading capacity of the mixing chamber shall be 70 % of its volume [3]. According to the TMR consumption (3 kg) for 100 goats every time, the bottom diameter and height of the mixing chamber were set to 1,000 and 1,300 mm, respectively, in this study. To prevent agglomeration of materials, the inclination angle of the sidewall of the mixing chamber shall be between 105° and 120° [11]. If the inclination angle is excessively large, the whole machine size increases, and the TMR is stirred unevenly, thus influencing the stirring effect.

Structural design of vertical screw: A vertical screw is mainly used to stir and rub TMR, aiming to mix components of TMR evenly. In this study, a conical vertical screw with small upper end and large bottom was applied. The TMR easily formed a convective cyclic movement in the mixing chamber, thus improving the mixing efficiency and avoiding agglomeration of TMR. In accordance with existing research results, the initial structural parameters were chosen, and the auger blade had a three-ring equal-pitch variable-diameter trochoid screw structure. The bottom diameter and the centre shaft sleeve diameter of the auger were set to 980 and 200 mm, respectively. The initial designed pitch ranged from 200 mm to 400 mm. The inclination angle (Z) at the bottom of the vertical screw was between 60° and 90°, and the auger structure is shown in Fig. 2.

The rotational speed of the vertical screw is the major factor influencing the stirring effect and processing speed of TMR [12, 13]. With reference to the critical rotational speed of vertical augers, the critical rotational speed [14, 15] of the vertical screw can be expressed as:

$$n = \frac{30}{\pi}\sqrt{\frac{g\tan(\alpha + \varphi_a)}{\mu_s r}} \tag{2}$$

$$\tan\alpha = \frac{S}{\pi d} \tag{3}$$

where n is the critical rotational speed of the vertical screw (r/min). α refers to the lift angle of the helical blade (°). φ_a is the frictional angle between materials and the blade surface of the vertical screw (°). μ_s denotes the friction coefficient between materials. S shows the pitch of the vertical screw (mm). d denotes the screw diameter at points where material particles lie in (mm).

Through an experimental test, $\varphi_a = 20.31°$ and $\mu_s = 0.68$, the minimum theoretical rotational speed was $n_{min} = 36.07$ r/min, the maximum theoretical rotational speed was $n_{max} = 116.31$ r/min. In consideration of the different properties of TMR, the critical rotational speed during simulation analysis could be 40-120 r/min.

2.3 Simulation analysis

Many factors may influence the mixing uniformity of TMR for dairy goats, mainly including the mixing ratio between forage and concentrated feeds and stirring time. Moreover, the structural size of the stirring device influence the mixing uniformity. In this study, a discrete element model of TMR for dairy goats will be established in the following text. The stirring process for different components in the stirring device was simulated, and the relevant influencing factors were analysed, thus identifying the optimal structural parameters.

Construction of the simulation model for TMR: The shape, volume, and physical properties of components in TMR for dairy goats influence the mixing process directly. Models of different components in TMR were constructed before the simulation analysis. The main components of fully mixed TMR for dairy goats included 35 % concentrated feeding materials, 55.0 % corn silage straw, and 10.0 % alfalfa hay. To simplify the simulation calculation, grains of concentrated feeding materials had relatively small geometric sizes, and they could be equivalent to spherical grains with a diameter of 2 mm is shown in Fig. 3 a. Corn silage (about 20 mm × 8 mm × 3 mm) is shown in Fig. 3 b and alfalfa hay (about 20 mm × 2.5 mm) is shown in Fig. 3 c were equivalent to the corresponding multirow and single-row spheres, respectively. The simulation models of TMR constructed in the pre-processing module of discrete software EDEM 2020 are shown in Fig. 3. The Hertz–Mindlin (no slip) model was chosen for the contact model of particles. In accordance with abundant tests and references [16-18], the material properties and contact parameters were acquired (Table I and Table II).

a) b) c)

Figure 3: Simulation model of grains.

Table I: Material properties.

Items	Steel	Alfalfa hay	Corn silage	Concentrated feeding materials
Density (kg/m^3)	7800	288.30	636.12	1197
Poisson's ratio	0.3	0.4	0.28	0.4
Shear elasticity	7e+10	5e+06	3.5e+07	1.37 e+08

Table II: Material contact parameters.

Items	Restitution coefficient	Sliding friction coefficient	Rolling friction coefficient
Alfalfa hay-steel	0.39	0.52	0.14
Alfalfa hay-corn silage	0.33	0.68	0.20
Alfalfa hay-alfalfa hay	0.30	0.65	0.24
Alfalfa hay-concentrated feeding materials	0.26	0.41	0.30
Corn silage-steel	0.39	0.66	0.18
Corn silage-corn silage	0.30	0.60	0.19
Corn silage-concentrated feeding materials	0.27	0.54	0.22
Concentrated feeding materials-steel	0.37	0.37	0.19

The 3D model of stirring device was built using Creo software, and it was input into EDEM 2020 software in *.stl* format.

Simulation test design: In this study, the coefficient of variation (C_V) of mixing uniformity (C_V) was used to describe the stirring uniformity. The smaller C_V is, the higher the uniformity of the stirring will be. Auger power, or known as mixing power, is lower at the same uniformity, and the stirring device shows better performance. The single-factor test levels are shown in Table III.

Table III: Factor levels in single-factor test.

Level	**Pitch of the vertical screw** (mm)	**Rotational speed of the vertical screw** (r/min)	**Bottom inclination angle of the vertical screw** (°)	**Inclination angle of the mixing chamber** (°)	**Pitch of the vertical screw** (mm)
1	200	40	60	105	60
2	250	60	70	110	70
3	300	80	80	115	80
4	350	100	90	120	90
5	400	120	-	-	-

In the post-processing module of EDEM, grains of various components were marked in different colours. The mixing zone was divided into six layers vertically from top to bottom (Fig. 4). Each layer was further divided into four zones by centring at the axis. The total number of grains in each zone and the quantity of grains of different components were calculated. In this study, C_V of concentrated feeding materials was used to express the mixing uniformity [19], which can be expressed as follows:

$$C_V = \frac{S}{M} \times 100\% \tag{4}$$

where C_V refers to the C_V of mixing uniformity (%). S is the standard deviation of the proportion of the number of concentrated feeding material grains in the total grain number in the division zone. M is the mean of the proportion of the number of concentrated feeding material grains in the total grain number in the division zone.

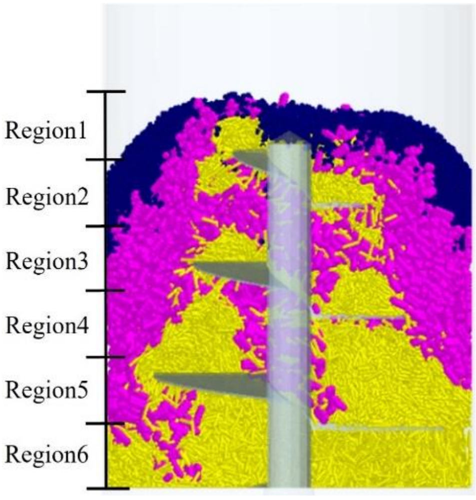


Figure 4: Distribution pattern of vertical statistical regions of particles in the mixing chamber.

The torque of the vertical screw during stirring process was output using the post processing module of EDEM, and its mean (T) was calculated [19, 20]. It was introduced into the mixing power in the process (P), as shown as follows:

$$P = \frac{nT}{9549} \tag{5}$$

where P is the mixing power (kW). n is the rotational speed of the screw auger (r/min). T is the average torque of the vertical screw in the stirring process (N·m).

3. RESULTS

3.1 Analysis of simulation design results

Pitch of the vertical screw: The simulation conditions were as follows: $L = 70\,\%$, $n = 60$ r/min, $\beta = 110°$, $Z = 80°$, and $S = 200$ mm – 400 mm.

The relationship between C_V and S is shown in Fig. 5 a. With the increase in stirring time, the components of TMR were mixed more evenly, and C_V was lower. When $S < 300$ mm, the time to reach the uniform state of TMR was shortened with the increase in pitch. The shortest time was achieved at 300 mm of the pitch. When $S > 300$ mm, it showed insignificant influences on the time to reach the mixing uniformity of TMR. It is because with the increase of S, the TMR among pitches increased, thus increasing the constant speed of TMR and shortening the time to reach mixing uniformity.

The relationship between P and S is shown in Fig. 5 b. With the increase of S, the P presented a linear growth because the increased pitch induced increased stirring volume. Given the fixed rotational speed of the auger, the power consumption would surely increase.

Based on the required time and mixing power to reach mixing uniformity of TMR, $S = 300$ mm was selected for follow-up studies.

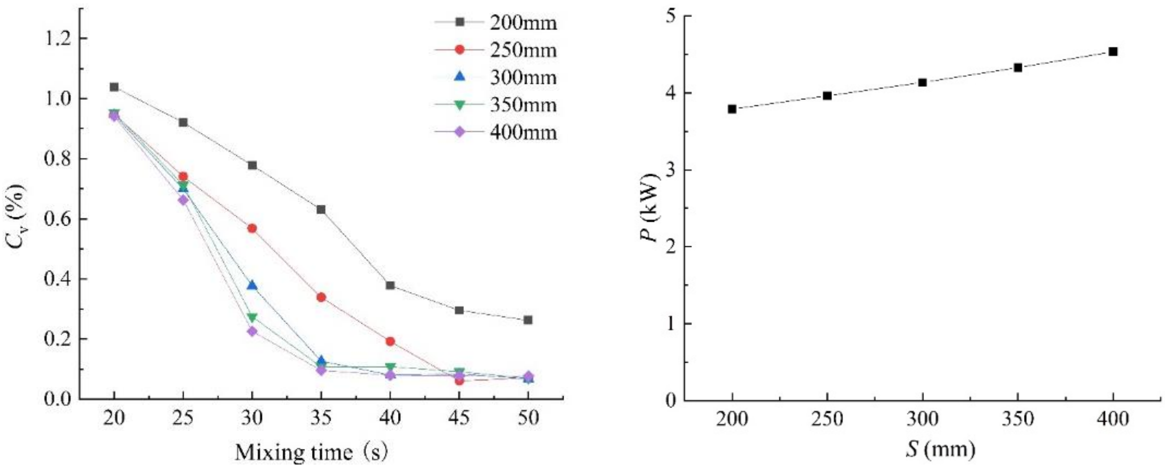
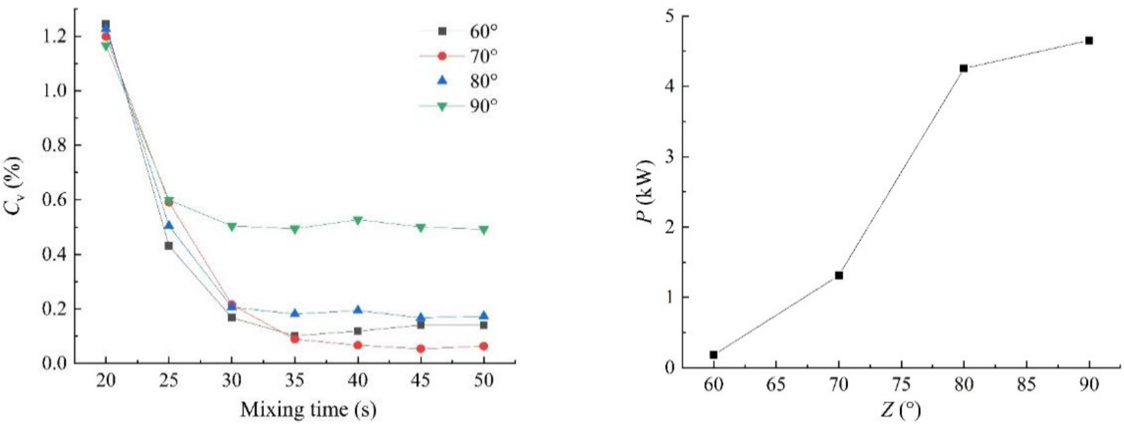


Figure 5: Effects of the pitch of the vertical screw on C_V and mixing power.

Bottom inclination angle of the vertical screw: The simulation conditions were as follows: $L = 70\,\%$, $n = 60$ r/min, $S = 300$ mm, $\beta = 110°$, and $Z = 60°$-$90°$.

The relationship between C_V and Z is shown in Fig. 6 a. As the Z increased, C_V first decreased and then increased. When $Z = 70°$, C_V reached the minimum, and TMR was mixed most evenly. The changes in the bottom inclination angle of the auger reflected that the width of auger blades decreased gradually from bottom to top. When $Z < 70°$, the blade at the upper of the auger was relatively narrow and had a small contact area with TMR. The lifting volume of TMR and the lifting efficiency were relatively low. When $Z > 70°$, the diameter of the upper helical blade of the auger was relatively large, whereas the gap between the screw structure and the side wall of the mixing chamber was relatively small. Owing to the insufficient cyclic space of TMR, the mixing uniformity was somewhat poor.

The relationship between the P and Z is shown in Fig. 6 b. P was positively related to Z. P increased dramatically when $Z > 70°$. The power variation tended to be stable when $Z > 80°$. From the perspective of energy-saving environmental protection, $Z = 70°$ was selected for follow-up studies.



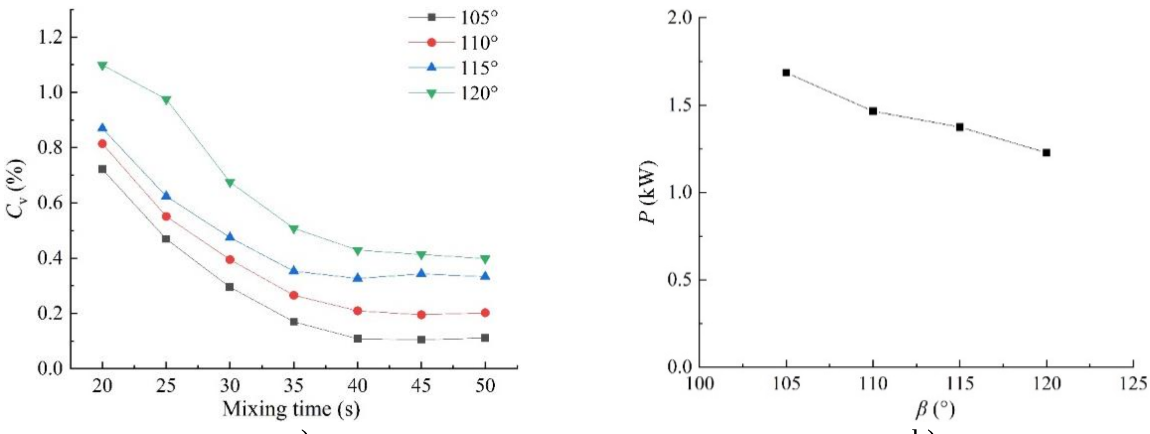
a) b)

Figure 6: Effects of the bottom inclination angle of the vertical screw on C_V and P.

Inclination angle of the sidewall of the mixing chamber: The simulation conditions were as follows: $L = 70$ %, $n = 60$ r/min, $S = 300$ mm, $Z = 70°$, and $\beta = 105°$-$120°$.

The relationship between C_V and β is shown in Fig. 7 a. With the increase of β, C_V increased gradually, and TMR was mixed more unevenly. When β increased, the contact ratio between the vertical screw and TMR decreased, and the TMR between the auger and the sidewall of the mixing chamber was not squeezed effectively. Consequently, a forced cyclic movement was not formed, most TMR was not mixed, and the mixing uniformity was low.

The relationship between P and β is shown in Fig. 7 b. P was negatively related to β, mainly because most TMR was stacked near the sidewall of the mixing chamber far away from the auger when β increased. When the auger rotated, the volume of TMR that moved with the auger was low, and the mixing power decreased. To assure the mixing effect of TMR, $\beta = 105°$ was selected for follow-up studies.



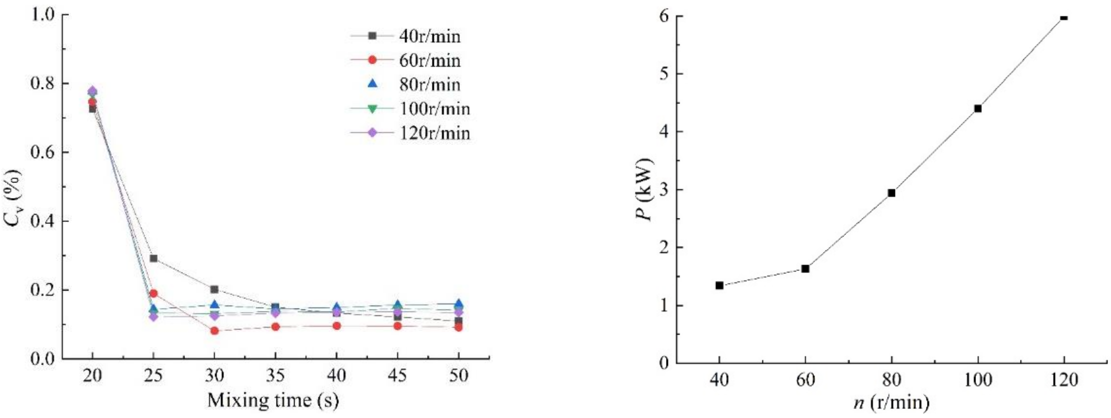
a) b)

Figure 7: Effects of the inclination angle of the sidewall of the mixing chamber on C_V and P.

Rotational speed of the vertical screw: The simulation conditions were as follows: $L = 70$ %, $S = 300$ mm, $\beta = 105°$, $Z = 70°$, and $n = 40$ r/min-120 r/min.

The relationship between C_V and n is shown in Fig. 8 a. The mixing uniformity was influenced by n slightly, and the minimum mixing uniformity was reached at different times. When n increased from 40 r/min to 80 r/min, the time to reach the minimum C_V of mixing uniformity declined continuously. When n increased from 80 r/min to 120 r/min, a small difference in C_V of mixing uniformity remained. The reason was that with the increase of n, increased the axial and radial moving speeds of fodders and decreased the time to reach the mixing uniformity.

The relationship between *P* and *n* is shown in Fig. 8 b. *P* increased continuously when *n* increased from 40 r/min to 120 r/min, and it increased dramatically as *n* from 60 r/min to 120 r/min. In consideration of power consumption and system stability, *n* = 60 r/min was selected for follow-up studies.



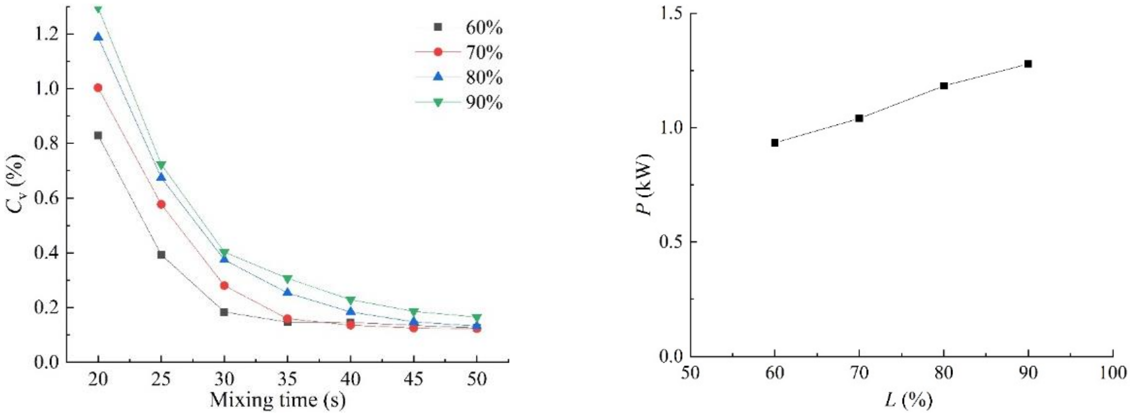
a) b)

Figure 8: Effects of the rotational speed of the vertical screw on C_V and P.

Loading rate of the mixing chamber: The simulation conditions were as follows: $n = 60$ r/min, $S = 300$ mm, $\beta = 105°$, $Z = 70°$, and $L = 60$ %-90 %.

The relationship between C_V and *L* is shown in Fig. 9 a. When *L* increased from 60 % to 90 %, the time to reach the minimum C_V increased gradually. Specifically, the minimum C_V was basically constant when *L* was 60 % and 70 %. As the *L* increased from 70 % to 90 %, the minimum C_V increased gradually, whereas the mixing uniformity of TMR declined. With the increase in *L*, the liquidity of component particles in the mixing chamber decreased, requiring more time to reach the mixing uniformity of TMR. As a result, the mixing uniformity in the same mixing time deteriorated.

The relationship between *P* and *L* is depicted in Fig. 9 b. When *L* increased from 60 % to 90 %, the mixing power increased continuously. With comprehensive consideration of production efficiency and the weight of mixing TMR per batch, *L* = 70 % was selected for follow-up studies.



a) b)

Figure 9: Effects of loading rates on C_V and *P*.

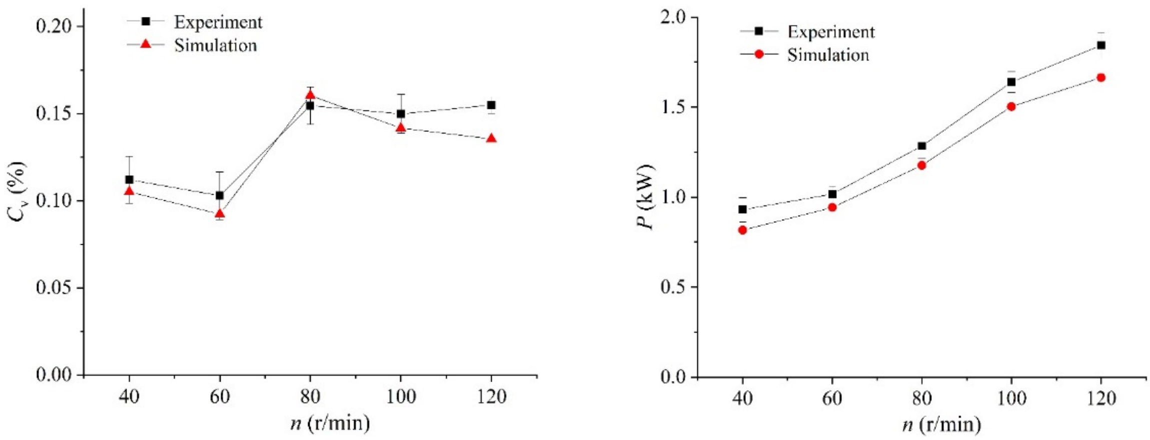
3.2 Experimental verification

Experimental conditions and test indexes: The testbed of the stirring device is shown in Fig. 10. The major parameters of key parts included the following: bottom diameter of the mixing chamber is 1000 mm, height is 1300 mm, bottom diameter of the mixing chamber is 980 mm, pitch of the vertical screw is 300 mm, inclination angle of the sidewall of the mixing chamber is 105°, and bottom inclination angle of the vertical screw is 70°.

In this experiment, C_V was chosen as the index to evaluate the mixing performance of the stirring device. For the convenient statistics of mixing uniformity, rice was chosen as the tracer [21] and added at 3 % of the loading rate of the mixing chamber. When TMR components were loaded in, rice was scattered on the upper surface of mixing TMR uniformly. After the stirring, 10 samples (100 g per sample) were collected uniformly. A statistical analysis on rice particles in each sample was carried out to calculate C_V.

Figure 10: Testbed of the stirring device.

Effects of the rotational speed of the vertical screw on mixing uniformity and mixing power: The experimental conditions were as follows: $L = 70$ % and mixing time is 8 min. The n increased from 40 r/min to 120 r/min at a rate of 20 r/min.



a) b)

Figure 11: Effects of the rotational speed of the vertical screw on C_V and P.

The relationship between C_V and n is shown in Fig. 11 a. When $n = 60$ r/min, the minimum C_V was achieved in both experiment and simulation analysis. Subsequently, C_V increased significantly with the increase in n, followed by small changes. Increasing n could increase the weight of stirring TMR to some extent, thus improving the mixing effect. However, the centrifugal force of TMR grains in moving state increased when n was excessively large. TMR grains moved toward the surrounding areas rather than moving upward, which influenced the lifting efficiency of TMR by the helical blades directly. Given the same rotating speed, the error between the experimental C_V and simulation results was only 3.62 %-12.53 %, indicating that the results are basically consistent.

The relationship between P and n is shown in Fig. 11 b. The P increased continuously when n increased from 40 r/min to 120 r/min. Given a n, the P in the experiment was 7.33 %–12.17 % higher than that in the simulation analysis. The variation trends of the experimental results and simulation analysis results are basically consistent, mainly because in practical mixing process, the grain size and shapes of components in TMR are more complicated and diversified. Component grains intertwine, thus increasing the acting force between the auger and TMR grains and further increasing the mixing power.

Effects of the loading rate of the mixing chamber on mixing uniformity and mixing power: The experimental conditions were as follows: mixing time is 8 min, $n = 60$ r/min. The L increased from 60 % to 90 % at the rate of 10 %.

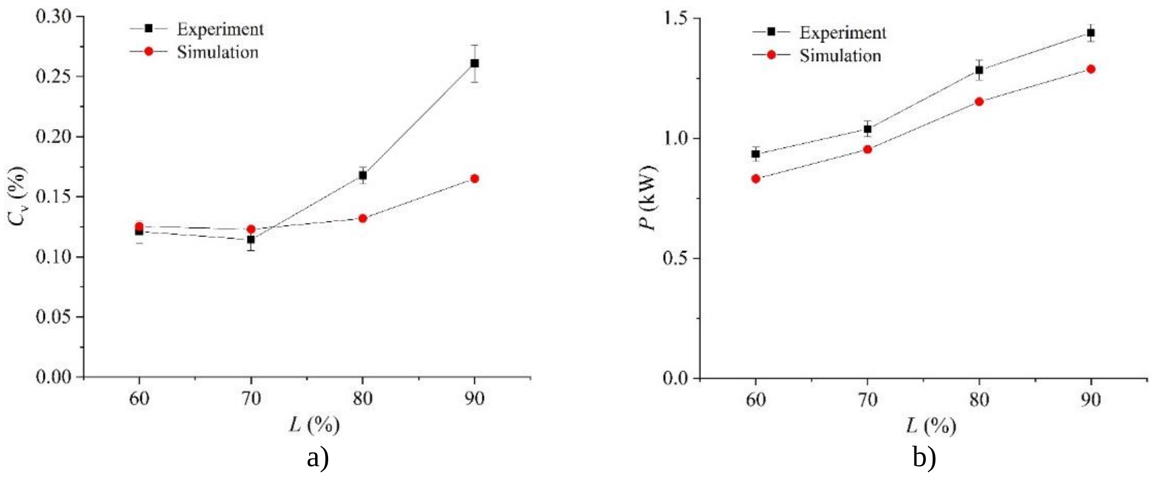


Figure 12: Effects of loading rate on C_V and P.

The relationship between C_V and L is shown in Fig. 12 a. C_V increased with the increase in L, whereas the daily uniformity decreased. The reason was that the loading height of TMR inundated the vertical screw when L was higher, and the liquidity of TMR after disturbance of the vertical screw declined. The pushing effect of the top TMR by the auger was not obvious, and the mixing effect deteriorated. Fig. 12 b demonstrates that the variation trends of the experimental results and simulation results are basically consistent. However, a great difference in C_V occurred when L = 80 %-90 %. When the experimental results exceeded the simulation results by 3.43 %-36.74 %, the uniformity of TMR was poorer because markers in the experiment were only scattered on fodder surface. Hence, some of the upper markers stayed at upper positions, without being stirred.

The relationship between P and L is shown in Fig. 12 b. With the increase in L, P for mixing TMR increased accordingly. The variation trends of P between the experiment and simulation analysis are basically consistent. However, when L was the same, the experimental P was 8.20 %-10.93 % higher than that in the simulation analysis. According to the analysis, the difference in mixing power increased because of the different TMR grains between the experiment and simulation analysis.

In a word, the variation laws of C_V of TMR in the single-factor tests of the stirring device are basically consistent with those in the simulation analysis. The mixing uniformity of TMR fluctuated with the increase in n. With the increase in L, the mixing uniformity of TMR deteriorated continuously. In the experiment, C_V = 13.03 %, P = 1.41 kW. In the simulation analysis, C_V = 12.95 %, P = 1.35 kW. The experimental results and simulation results are basically consistent, meeting the requirements for mixing uniformity of DG-T 054-2019 fully mixed TMR preparation machines.

4. CONCLUSION

In this study, discrete element models of TMR for dairy goats were established. The variation laws of the structural parameters of the vertical screw stirring device and the working parameters with the mixing uniformity of TMR and mixing power were analysed. On this basis, the optimal parameters were identified. Lastly, an experimental verification was carried out. The following conclusions were drawn:

(1) The mixing uniformity of TMR first increased and then declined with the increase in the bottom inclination angle of the auger, whereas it decreased with the increase in the inclination angle of the sidewall of the mixing chamber and the loading rate of the mixing chamber. It was influenced by the pitch and rotational speed of the vertical screw slightly. The mixing power was positively related to the pitch, bottom inclination angle, and rotational speed of the vertical screw and the loading rate of the mixing chamber. On the contrary, it was negatively related to the inclination angle of the sidewall of the mixing chamber.

(2) The optimal structural parameters for the stirring device determined by simulation numerical analysis were as follows: pitch of the vertical screw is 300 mm, bottom inclination angle of the vertical screw is 70°, and inclination angle of the sidewall of the mixing chamber is 105°. The optimal working parameters were as follows: rotational speed of the vertical screw is 60 r/min and loading rate of the mixing chamber is 70 %. This method effectively realized a quantitative analysis of the parameters.

(3) According to an experiment, C_V of mixing uniformity was 13.03 %, and that of mixing power was 1.41 kW. These results agreed well with the simulation results (12.95 % and 1.35 kW). The experiment could characterize the working performance of the system significantly, and it was convenient for reasonable regulation.

Given that many factors may influence the movement of TMR grains in the stirring and mixing processes, such as the properties of different components, this method has important significance to follow-up studies on mixing different TMR components and improving the applicability of the generated stirring device.

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