DESIGN AND EXPERIMENT OF SEGMENTED TYPE MIXER WITH DOUBLE SPIRAL RIBBON FOR AGRICULTURAL WASTE
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分段式双螺带农业废弃物搅拌装置设计与试验

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ABSTRACT
In this study, a segmented type mixer with double spiral ribbon was designed to destroy choking and accumulation of agricultural waste in the mixing process, by improving the mixing uniformity and reducing the residual amount of maize straw and cow dung. To determine the optimal working parameters of the mixer, the ternary quadratic regression orthogonal rotation combined experiment was carried out by using the mixing uniformity and residual rate of material as the evaluation indexes and the spindle speed, full coefficient and mixing time as the influencing factors. The results showed that the order of the influences on the mixing uniformity was spindle speed>mixing time>fullness coefficient, and the order of the influences on the residual rate of material was fullness factor>spindle speed>mixing time. The study established a regression model of influencing factors and evaluation indexes, and analysed the influence of significant factors and their interaction on evaluation indexes. The optimum combination after parameter optimization based on response surface method was determined to be as follows: spindle speed of 38.00rad/min, full coefficient of 55.00%, mixing time of 9.33min. While the mixing uniformity and residual rate of material corresponding to the verification test were 91.25% and 95.19%, respectively, the relative error of the predicted result was less than 0.5%. The study meets the requirements of mixing agricultural waste materials to make fertilizers, and provides technical solutions for improving the localized resource utilization of agricultural waste.

摘要
针对农业废弃物搅拌过程壅堵和积料的问题，本研究为提高玉米秸秆和牛粪混合均匀性、降低物料残留量，设计了一种分段式、双螺带搅拌装置。为确定装置最佳工作参数，以主轴转速、充满系数和混合时间为试验因素，以混合均匀度和物料残留率为评价指标，采用三元二次回归正交旋转组合试验方法进行试验与响应面分析。结果表明：影响混合均匀度的主次因素为：主轴转速＞混合时间＞充满系数，影响物料残留率的主次因素为：充满系数＞主轴转速＞混合时间。建立试验因素与评价指标的回归模型，分析显著因素及其交互作用对评价指标的影响。基于响应面法进行参数优化，确定最终优化参数组合为：主轴转速 38.00rad/min，充满系数 55.00%，混合时间 9.33min，对应验证试验的混合均匀度和物料残留率分别为 91.25%和 95.19%，与模型预测结果相对误差小于 0.5%。该研究满足农业废弃物料制肥的混配要求，为提高农业废弃物属地化资源利用提供技术方案。

INTRODUCTION
With the high-quality development of China’s agriculture and rural areas, more and more attention has been paid to the agricultural ecological environmental problems caused by agricultural wastes from non-intensive planting and breeding, and the decrease in the quality of cultivated land caused by long-term large-scale use of chemical fertilizers (*Wang et al., 2020; Wang et al., 2017*). Decomposing and returning the solid biomass such as straw and livestock manure to the field is a significant means to coordinate agricultural waste pollution and soil nutrient deficiency (*Chai et al., 2019; Zhang et al., 2020*). By using local straws and livestock manure to produce organic fertilizer or soil amendments through small-scale compost decomposing, the agricultural organic waste can be returned to the field accelerated, which is brought by decentralized small and medium agricultural production.

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It is a technological method to increase the conversion efficiency of agricultural waste resources and improve the physical and chemical properties of the soil. The mixing effect, during the small-scale compost decomposing technology, affects the working process of fertilizer spreading machine and the quality of fertilizer (*Ştefan et al., 2019; Cârdei et al., 2019*). Intermittent low-speed mixing can reduce energy consumption and improve the fermentation effect, by studying the influence of different mixing parameters on the power consumption of the equipment and the fermentation effect of cow manure (*Peter et al., 2020; Li et al., 2013*). The medium-speed mode of the equipment can speed up the mixing process of bulk materials, by studying the flow characteristics of straw materials of the conveying process over a rough surface, which provides help for the design of spiral screw mixing system (*Pylypaka et al., 2017; Xue et al., 2017; Naumenko et al., 2018*). The research on the mechanical behaviour of maize straw pith and the bulk particle motion kinematics in the screw conveyor-mixer provided theoretical support for the design of crop-mechanical mixing-system (*Ștefan et al., 2018; Hewko et al., 2015; Zhang et al., 2017*). Continuous-flow conveyors could transport simultaneously during mixture process, which provided a mean of choosing cost-effective operating modes of a conveyor-mixer (*Hevko et al., 2017*).

In order to effectively improve the applicability of agricultural waste mixing equipment, this paper designs a segmented type mixer with double spiral ribbon, which is able to improve the mixing uniformity and reduce the residual. On the basis of performed finite element analysis on the mixing mechanism, from the material mixing mechanism point of view, the material-mechanical interaction is analysed, whereby the whole machine structure and key components is designed. Moreover, through the three-dimensional quadratic regression orthogonal rotation combined experiment and field verification test, the working parameters of the prototype were optimized, and the working performance was verified.

MATERIALS AND METHODS

The whole design and working principle

The segmented type mixer is mainly composed of the spiral ribbon structure, mixing chamber, transmission system, motor, and reducer. Its structure is as shown in Fig.1. The overall design dimensions are 1660mm×600mm×1100mm (length × width × height) and the overall mass is 160kg. The capacity of the mixing chamber is 0.40m^3, the power of the motor is 3.0kW, and the productivity is about 500kg/h.

The mixing chamber is composed of a rectangular parallelepiped in upper part and a semi-cylinder in lower part. According to the research on the length-to-width ratio of the mixing chamber (*Chen et al., 2004*), when the capacity of the mixing chamber is determined, the length-to-width ratio of the mixing chamber is one of the main parameters. The length of the mixing chamber is 1000mm, the width and lower diameter are all 500mm, and the upper part is 550mm high.

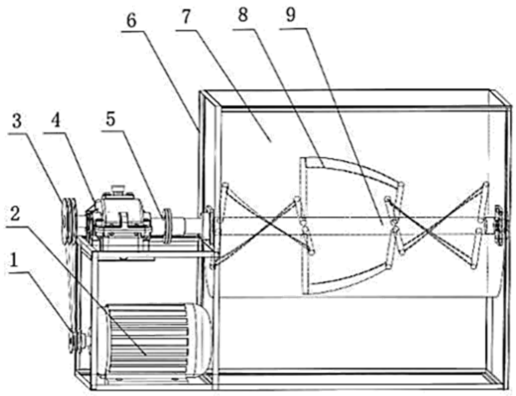


Fig. 1 - Diagram of the overall structure for the mixer

1- The first belt wheel; 2- The motor; 3- The second belt wheel; 4– Reducer; 5– Coupling; 6– Frame; 7- Mixing chamber;8- Spiral ribbon structure; 9- Mixing spindle

Belt transmission is the main transmission mode of the mixer, while the motor transmits power to the mixing spindle through the reducer and coupling. The machine's transmission scheme is shown in Fig.2. During work, the filamentous straw and the cow dung after cleaning are fed from the opening in the upper part of the mixing chamber. The segmented and reversed double spiral ribbon mixing structure on the mixing spindle makes the material produce three-dimensional reciprocating mixing motion. In the mixing chamber, the mixing structure was divided into three segments in the horizontal direction: left, middle and right, and in the vertical direction, which was divided into two rotations: left-hand and right-hand. The direction of rotation is opposite in the same segment, and the left and middle segments are opposite to the right segment. Straw and cow dung are driven by the reverse spiral ribbon in the horizontal direction to produce convective motion, and are continuously divided by the rotating spiral ribbon in the vertical direction to produce shearing motion. Simultaneously, the different gravity of the straw and cow dung causes different movement speed and direction, which results in diffusion movement. That is, the left and right mixing ribbons push the material to the middle position of the mixing chamber, and the middle mixing ribbon pushes the material to both sides of the mixing chamber, whereby the material is gradually mixed in the mixing chamber, as shown in Fig.3. After the mixing is completed, open the discharge port at the lower part of the mixing chamber, and the material is discharged out of the chamber under the force of the spiral ribbon and its own gravity.

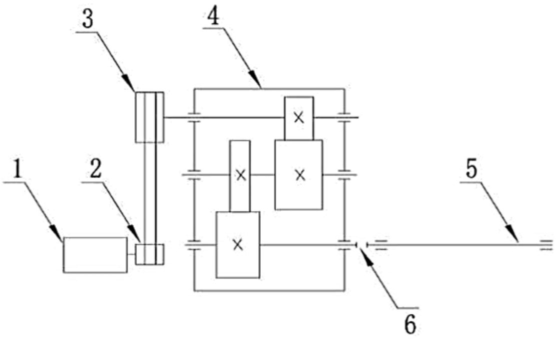


Fig. 2 - Structural diagram of the machine transmission scheme
1- Motor; 2- Small pulley; 3- Large pulley; 4- Reducer; 5- Stirring spindle; 6- Coupling

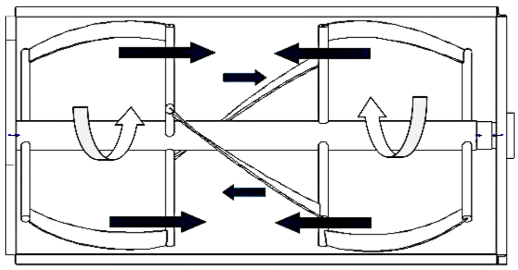


Fig. 3 - Schematic diagram of material mixing process

Design of key structural parameters

Design of mixing arm

Redundancy of mixing arms will affect the flow of materials in the mixing chamber, and increase the design length of the mixing spindle, thereby reducing the structural strength. When the number of mixing arms is small, the force of the mixing arms and mixing ribbons will increase when the material is pushed, which will affect the mixing quality and working efficiency of the mixer (*Liu et al., 2019*). Considering the relationship between the phase angle of the mixing arm and the number of mixing arms, as shown in Fig.4, the design value of the phase angle of the mixing arm is 60°, and the number of mixing arms is 4 groups.

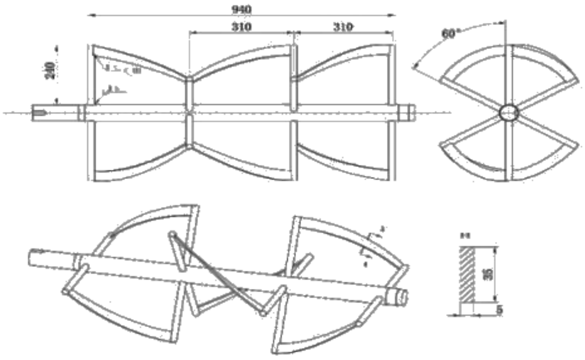


Fig. 4 - Mixing arm and ribbon arrangement

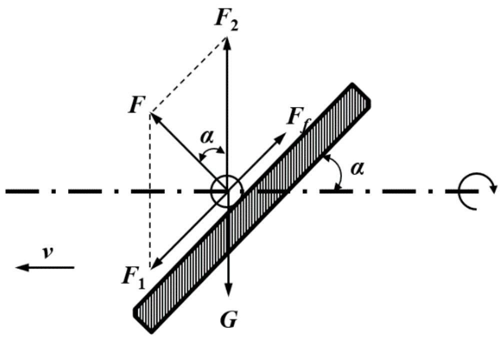


Fig. 5 - Material point force diagram

Design of spiral ribbon

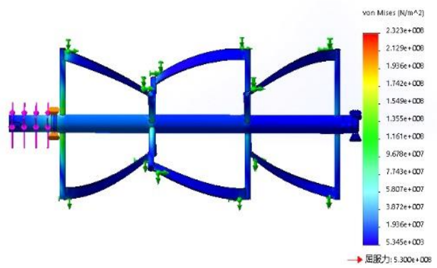
Referring to the design of the spiral ribbon stirring device, the spiral ribbon is a single strip, and the design blade width is 35mm, the thickness is 5mm, and the length is 320mm. As it is shown in Fig.5, the installation angle of the ribbon refers to the acute angle α between the inclined surface of the ribbon and the stirring axis. Simplify the material into a mass point, then the force on the mass point is: gravity G, driving force F and friction force F_f, f is the friction coefficient, decomposing F into the surface direction force F_1 and the vertical axis direction force F_2. To achieve axial movement of the material, F_1 must be greater than or equal to F_f, that is:

$$F \cdot \tan\alpha - F \cdot f \geq 0 \tag{1}$$

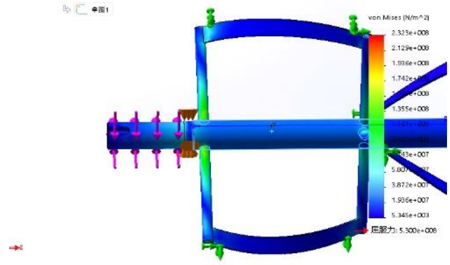
then, the installation angle of the ribbon $\alpha \geq \arctan \cdot f$. Take the friction coefficient as 0.55, so $\alpha \geq 29°$. In order to increase the movement of the material in the mixing chamber, the design value of the installation angle of the ribbon α is 45°.

Static stress analysis

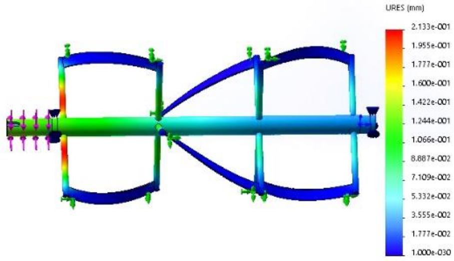
In this design, the mixing structure and mixing shaft were made of No. 45 steel. The finite element analysis model of the mixing equipment had a total of 17,878 units and 33841 nodes. As it is shown in Fig.6, the main stress parts, main deformation and displacement areas of the mixing equipment were the power input position and the connection between two mixing arms. The maximum stress was 232MPa, which meted the requirements of the material permission range, where the mixing arm and the mixing spindle would not bend and break under the jamming condition.



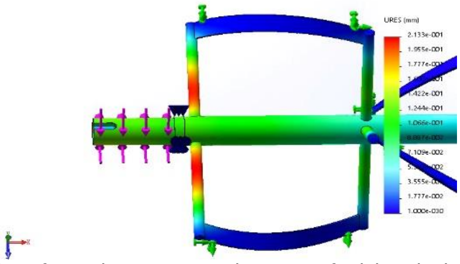
a. Stress diagram of stirring device



b. Stress concentration area diagram of mixing device



c. Deformation diagram of stirring device

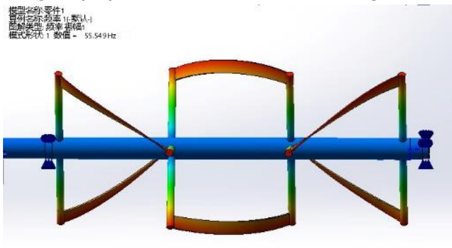


d. Deformation concentration area of mixing device

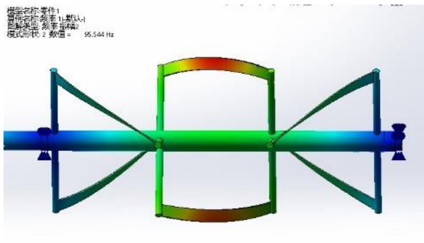
Fig. 6 - Static stress analysis results of mixing mechanism

Modal analysis

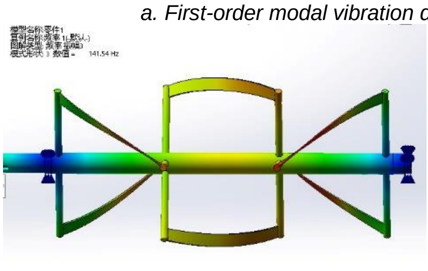
Because of the presence of vibration sources during work, it is necessary to conduct a modal analysis of the mixing equipment, as shown in Fig.7.



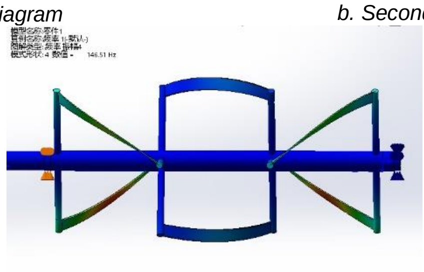
a. First-order modal vibration diagram



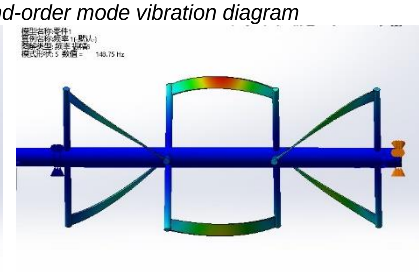
b. Second-order mode vibration diagram



c. Third-order mode vibration diagram



d. Fourth-order mode vibration diagram



e. Fifth-order mode vibration diagram

Fig. 7 - Modal vibration pattern of the first five orders for the stirring mechanism

The first five orders natural frequencies of the extraction were 55.549 Hz, 95.544 Hz, 141.54 Hz, 146.51 Hz, and 148.75 Hz. It shown that with the increase of the mode order, the natural frequency of the mixing equipment also increased, but the increase speed was gradually reduced. The design maximum speed of the mixing equipment was 45 rad/min, which was much smaller than the critical speed of 3332.94r/min under the minimum natural frequency, so the mixing equipment would not cause resonance in the actual working process.

Experiment design

The experiment was conducted at the Northeast Facility Horticultural Engineering Scientific Observation and Experimental Station of Shenyang Agricultural University. The experiment maize straw was harvested in 2018 at North Mountain Scientific Research Base of Shenyang Agricultural University, and the experiment cow dung was taken from surrounding farmers.

Before the experiment, it was randomly sampled and determined the moisture content range of maize straw and cow dung stored under natural conditions, using an electronic analytical balance (Germany Sartorius QUINTIX224-1CN) and a digital display electric heating constant temperature drying oven (Shanghai Yangguang Experimental Instrument Co., Ltd. 101-0A) and other equipment. The moisture content of maize straw was 15.36%, and the moisture content of cow dung was 65.12%. The ratio of straw to cow dung was 3:2 during the experiment. The experiment selects mixing uniformity and material residual rate as experiment indicators. According to the study of the detection methods and mixing characteristics of mixing uniformity (*Yu et al., 2015; Wang et al., 2013*), physical method was used in the experiment, and the bean with relatively small particle size and mass as tracers to detect mixing uniformity. The corresponding value of the tracer mass was measured each time $X_1, X_2, X_3, \ldots, X_{10}$ calculating the mean and standard deviation. The mixing uniformity was calculated according to formula (2).

$$M = (1 - \frac{S}{\overline{X}}) \times 100\% \quad (2)$$

where M is the mixing uniformity, %; S is the sample standard deviation; $\overline{X}$ is the sample marker average.

The detection method of the material residue rate is to measure the quality of the material put into the mixer and the quality of the material discharged from the mixer, and calculate the material residue rate according to formula (3).

$$E = (1 - \frac{T_1 - T_2}{T_1}) \times 100\% \quad (3)$$

where E is material residual rate, %; T_1 is the quality of the material put into the mixer, kg;

T_2 is the quality of the material discharged from the mixer, kg.

The experiment selected the spindle speed, the full coefficient and the mixing time as the experiment factors, and carries out the ternary quadratic regression orthogonal rotation combination experiment. According to the analysis of the aforementioned documents and the mixing process, the value range of each factor and the experiment factor levels were shown in Table 1. The experiment equipment and materials were shown as Fig.8.

Factors and levels of combination experiment **Table 1**

Levels	Factors		
	Spindle speed [rad·min^{-1}]	Full coefficient [%]	Mixing time [min]
	x_1	x_2	x_3
1.682	45.00	80.00	11.00
1	40.95（41.00）	71.89 (72.00)	9.78（9.80）
0	35.00	60.00	8.00
-1	29.05（29.00）	48.11（48.00）	6.22（6.20）
-1.682	25.00	40.00	5.00
△j	5.95（6.00）	11.89（12.00）	1.78（1.80）

Note: The parameters in parentheses were the parameters taken in the experiment. Adjusted the calculation results according to the feasibility of actual operation, and taken the values in parentheses.

Fig. 8 - Experimental equipment and materials

RESULTS

Experiment results and inspection

A total of 23 groups of experiment were considered, and each group was repeated three times. The results were taken as the average value. The experiment scheme design and result analysis were shown in Table 2.

The quadratic polynomial regression models among the spindle speed (x_1), full factor (x_2), mixing time (x_3), mixing uniformity (Y_M) and material residue rate (Y_E) were established. The following regression equations were obtained:

$$Y_M=-21.814+4.054x_1+1.859x_2-3.830x_3+0.014x_1x_2+0.025x_1x_3+0.080x_2x_3-0.071x_1^2-0.025x_2^2-0.090x_3^2 \quad (4)$$

$$Y_E=+49.791-1.193x_1-0.361x_2-3.021x_3+0.004x_1x_2-0.016x_1x_3+0.016x_2x_3+0.014x_1^2+0.001x_2^2+0.145x_3^2 \quad (5)$$

Significance test and analysis of variance were performed on the obtained ternary quadratic regression equation, and the results were shown in Table 3. The correlation coefficient R_M=0.98, R_E=0.95, the regression equation significance level F_{RM}=74.49, F_{RE}=28.05, the lack of fit test F_{LfM}=1.84, F_{LfE}=2.23, P_M=0.2115, P_E=0.1497 were all greater than 0.05 and the difference was not significant, indicating that the regression equations Y_M and Y_E was significantly with statistically significant.
The optimized regression equation after excluding insignificant terms such as x_1x_3 and x_3x_3 of Y_M and x_1x_3 of Y_E at the significance level of P=0.05 was:

$$Y_M=-21.814+4.054x_1+1.859x_2-3.830x_3+0.014x_1x_2+0.080x_2x_3-0.071x_1^2-0.025x_2^2 \quad (6)$$

$$Y_E=+49.791-1.193x_1-0.361x_2-3.021x_3+0.004x_1x_2+0.016x_2x_3+0.014x_1^2+0.001x_2^2+0.145x_3^2 \quad (7)$$

It can be seen from Table 3 that the spindle speed (x_1) and mixing time (x_3) had extremely significant effects on the uniformity of mixing and the residual rate of materials (P<0.01); the full coefficient (x_2) had a significant effect on the uniformity of mixing (P<0.05), which had extremely significant impact on the residual rate of materials (P<0.01); the interaction of spindle speed and full coefficient (x_1x_2), the interaction of fullness coefficient and mixing time (x_2x_3) had extremely significant impact on the uniformity of mixing (P<0.01), and significant impact on the residual rate of materials (P<0.05) .

Table 2

Experimental plan and results

No.	Spindle speed [rad·min^{-1}]	Full coefficient [%]	Mixing time [min]	*M* [%]	*E* [%]
1	1	1	1	90.25	93.16
2	1	1	-1	84.86	93.10
3	1	-1	1	86.31	96.69
4	1	-1	-1	87.44	94.48
5	-1	1	1	85.67	92.30
6	-1	1	-1	81.06	92.11
7	-1	-1	1	85.40	93.86
8	-1	-1	-1	87.87	93.13
9	1.682	0	0	85.47	94.59
10	-1.682	0	0	84.57	92.15
11	0	1.682	0	81.72	92.05
12	0	-1.682	0	82.32	96.22
13	0	0	1.682	92.37	94.72
14	0	0	-1.682	90.23	92.12
15	0	0	0	92.34	94.44
16	0	0	0	92.18	94.27
17	0	0	0	92.45	95.15
18	0	0	0	91.82	94.96
19	0	0	0	92.93	94.82
20	0	0	0	93.02	95.20
21	0	0	0	90.98	94.70
22	0	0	0	92.48	94.62
23	0	0	0	92.76	94.56

Table 3

Data significance experiment and analysis of variance

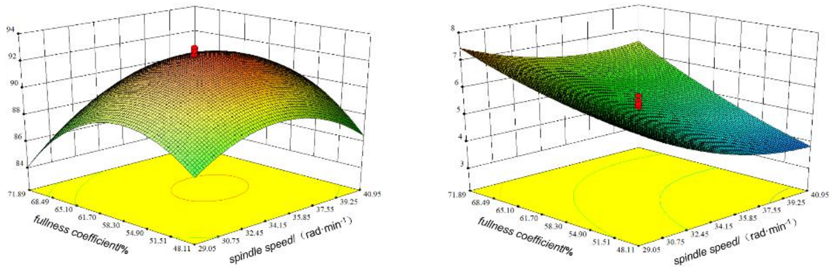
Source of variation	Mixing uniformity *M*				Material residual rate *E*			
	SS	DF	*F value*	*P value*	SS	DF	*F value*	*P value*
Model	350.62	9	74.49	<0.0001**	36.64	9	28.05	<0.0001**
x_1	7.88	1	15.07	0.0019**	7.53	1	51.89	<0.0001**
x_2	2.80	1	5.36	0.0375*	15.43	1	106.31	<0.0001**
x_3	7.32	1	14.00	0.0025**	4.20	1	28.91	0.0001**
x_1x_2	7.80	1	14.92	0.0020**	0.68	1	4.68	0.0497*
x_1x_3	0.56	1	1.07	0.3189	0.23	1	1.60	0.2276
x_2x_3	23.12	1	44.21	<0.0001**	0.90	1	6.21	0.0270*
x_1x_1	99.87	1	190.98	<0.0001**	3.66	1	25.19	0.0002**
x_2x_2	202.26	1	386.75	<0.0001**	0.71	1	4.89	0.0456*
x_3x_3	1.31	1	2.50	0.1379	3.39	1	23.38	0.0003**
Remaining	6.80	13			1.89	13		
Lack of Fit	3.64	5	1.84	0.2115	1.10	5	2.23	0.1497
Pure Error	3.16	8			0.79	8		
Sum	357.42	22			38.53	22		

Analysis of influencing factors

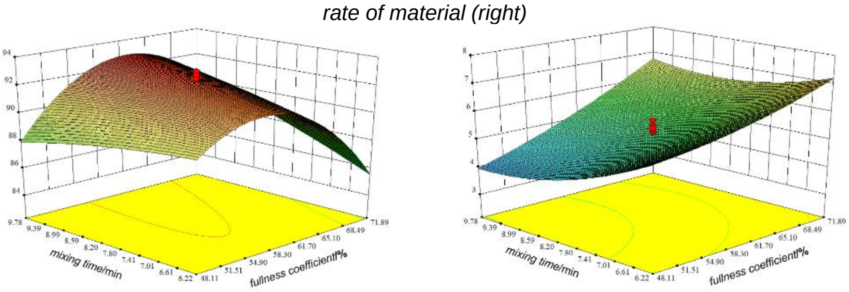
The calculation results of the response surface of each experiment factor and its interaction on the experiment index were shown in Fig.9. It can be seen from the figure that the primary and secondary order of the influence of each experiment factor on the mixing uniformity was spindle speed>mixing time>fullness coefficient, and the primary and secondary order of the influence of each experiment factor on the material residual rate was fullness coefficient>spindle speed>mixing time.

Figure 9a was the response surface diagram of the influence of the interaction between the spindle speed and the fullness coefficient on the mixing uniformity and the residual rate of the material when the mixing time was 0 level. It showed that when the spindle speed was constant and the fullness coefficient gradually increased within the experiment range, the mixing uniformity first increased and then decreased, and the material residue rate gradually increased. When the full coefficient was constant and the spindle speed gradually increased within the experiment range, the mixing uniformity first increased and then decreased, and the material residual rate gradually decreased. The peaks of the mixing uniformity and the material residual rate both appeared in the middle level range. This was because the fullness coefficient determined the total amount of material in the same time. When the fullness coefficient was at low level, the total amount of material was smaller, which caused the weakly active diffusion movement between the material, and the reduced shearing effect on the material of the ribbon, thereby the mixing effect was poor and the material was less attached to the inner wall of the mixing chamber and the mixing arms. When the fullness coefficient was at high level, there was more material in the mixing chamber, where the diffusion effect between materials was limited by the movement space. At the same time, under the same spindle speed, the spiral ribbon would disperse more the driving force of the material, thus affecting the convective mixing process and reducing the mixing effect, attaching more material to the mixing chamber wall and mixing arms. When the fullness coefficient was constant, appropriately increasing the spindle speed to increase the power input can improve the mixing effect. When the spindle speed was too high, during a larger input of power, the material moving speed was increased and the material residue was little. However, the material with different bulk densities was prone to form different mixed material areas in the mixing chamber, resulting in uncoordinated convection and diffusion conditions of the material in the horizontal and vertical directions, reducing the mixing effect.

Figure 9b was the response surface diagram of the influence of the interaction between the fullness coefficient and the mixing time on the mixing uniformity and the residual rate of the material when the spindle speed was 0 level. When the fullness coefficient was constant, and the mixing time was within the experiment range, the uniformity of mixing increased with the increase of mixing time, and the residual rate of material decreased with the increase of mixing time. When the mixing time was constant and the fullness coefficient gradually increased within the experiment range, the mixing uniformity first slowly increased and then decreased, and the residual rate of materials gradually increased. This is because when the spindle speed was constant and the input power was constant, the same fullness coefficient and the same material had the same force per mixing time; the mixing time increasing improved the mixing movement time of the material in the mixing chamber, further improving the mixing effect. But it also increased the time for the material to attach to the inner wall of the mixing chamber, which improved the adhesion strength and reduced the amount of material discharged.



a. The effect of the interaction between the spindle speed and the fullness coefficient on the uniformity of mixing (left) and the residual rate of material (right)



b. The effect of the interaction between fullness coefficient and mixing time on mixing uniformity (left) and material residual rate (right)

Fig. 9 - Response surface analysis of the factors interaction effect on the index

Parameter optimization and verification test

Set the target parameter the mixing uniformity and the material residual rate to maximize, and the factors parameter to the range of experiment to obtain the optimal working parameter combination of the segmented type mixer with double spiral ribbon: the spindle speed was 37.63rad/min, the fullness coefficient was 55.77%, and the mixing time was 9.33min, the overall operation effect being the best. The predicted mixing uniformity will be 91.7445% and the material residue rate will be 95.6798%.

In order to further verify the reliability and applicability of the mathematical model, the optimization results were tested and verified under the same experiment conditions, while the actual test results and the model prediction values were analysed for error. Considering the operability of the test, the optimization results were adjusted as follows: the spindle speed was 38.00rad/min, the fullness coefficient was 55.00%, and the mixing time was 9.33min, and three repeated tests were carried out to obtain the best working parameter combination. The average values of the test values of uniformity and material residue rate were 91.25% and 95.19%, respectively, which were close to the predicted values of the model. The relative error between the actual and predicted values didn't exceed 0.5%, indicating the established model and analysis results were valid.

CONCLUSIONS

In this paper, the mixing uniformity and material residue rate were used as the evaluation indicators of the mixing effect of the segmented type mixer with double spiral ribbon, and the influence of the spindle speed, fullness coefficient and mixing time under the mixing condition of maize straw and cow dung was studied. A response surface model was established, and the equipment's best working parameters were optimized through experiments, with the following conclusions:

1) Through the analysis of the mixing process of agricultural wastes, the segmented type mixer with double spiral ribbon was divided into three sections in the left, middle and right anti-spiral direction in the horizontal direction, and two sections in the anti-rotation direction in the vertical direction, so that the material in the three-dimensional reciprocating mixing movement was realized in the mixer to enhance the mixing effect of the material. The finite element analysis of the mixing mechanism was carried out to verify the feasibility of equipment design and operational reliability.

2) Through the ternary quadratic regression orthogonal rotation combination experiment, the mixer parameter optimization and verification tests were carried out, and the regression equation between the impression factors and the indexes was established and optimized. The influence of the factors and their interaction on the mixing effect and the law were analysed too.

The best working parameters of the equipment were: spindle speed 38rad/min, fullness coefficient 55%, mixing time 9.33min, upon which the mixing effect was the best, when the time mixing uniformity and material residue rate reached 91.25% and 95.19%. Respectively, it met the requirements of agricultural waste fertilizer production technology and had better performance.

This study only conducted related research on the mixing parameters and mixing effects of maize straw and cow dung under the experimental conditions. In the later stage, it is necessary to increase different types of straw and livestock manure and their interaction with mechanical structures and materials to conduct in-depth research to improve equipment applicability and reliability.

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