RESEARCH ON THE INFLUENCE OF EXTRUSION PARAMETERS ON SOLID-LIQUID SEPARATION PERFORMANCE OF LIVESTOCK MANURE AND OPTIMIZATION OF PARAMETERS
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畜禽粪污螺旋挤压脱水装置参数优化设计与试验

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ABSTRACT
Solid-liquid separation is essential for utilizing livestock and poultry manure, impacting greenhouse gas emissions and pollution control. This study aimed to address the high water content and low efficiency issues in screw extrusion solid-liquid separation technology. A screw separator was designed, and a Box-Behnken test scheme was used to optimize parameters with dairy manure as the test object. The study identified extender length, screw rotation speed, and counterweight mass as the influencing factors, with extrudate water content and solids extraction rate as evaluation indices. A quadratic regression model was established to describe the relationships between the influencing factors and evaluation indices. Optimal parameters were determined as: extender length=10 cm, screw rotation speed=55 r/min, and counterweight mass=34.73 kg. The predicted extrudate water content was 65.44 %, and solids extraction rate was 2.39 m³/h. Validation tests showed an average extrudate water content of 67.71 % and solids extraction rate of 2.10 m³/h, with relative errors of 3.3 % and 9.6 % respectively. The model's reliability was confirmed, providing a reference for designing livestock and poultry manure screw extrusion separators.

摘要
固液分离是畜禽粪便资源化利用的关键共性环节，对控制温室气体排放和环境污染治理具有重要意义。针对螺旋挤压固液分离技术存在的挤出物含水率偏高、处理效率较低的问题，本研究设计了一种螺旋挤压脱水装置，以奶牛粪为试验对象，采用 Box-Benhnken 试验方案开展了参数优化研究。以延长器长度、螺杆转速、配重重量为影响因素，以挤出物含水率和固形物提取率为考核指标，建立了影响因素与考核指标之间的二次回归模型。通过多目标优化函数，确定一组最佳参数组合为：延长器长度=10cm，螺杆转速=55r/min，配重重量=34.73kg，此时挤出物含水率预测值为 65.44%，固形物提取效率预测值为 2.39m³/h。验证试验结果表明，在最优参数组合下，挤出物含水率均值为 67.71%，与预测值相对误差为 3.3%。固形物提取效率均值为 2.10 m³/h，与预测值的相对误差为 9.6%。两个考核指标的实测值与理论预测值均＜10%，表明建立的二次回归模型可靠，可用于参数优化。研究结果可为畜禽粪污螺旋挤压分离机的设计提供参考。

INTRODUCTION
Livestock and poultry manure is one of the most important factors leading to ecological damage and environmental pollution, and is also the second largest source of greenhouse gas emissions from farms *(Aguirre-Villegas et al., 2017)*. For several consecutive years, the Chinese government has been introducing new policies with the aim of increasing the resource utilization of livestock and poultry manure. Solid-liquid separation (compression dewatering) machines are among the core equipment for livestock and poultry manure management and resource utilization, representing a current research hotspot and priority area *(Camilleri-Rumbau et al., 2021; Wu et al., 2021; Zhang et al., 2022)*.

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After dewatering, dry solids and low impurity filtrate are obtained, which facilitates subsequent management, disposal and field utilization, and reduces the cost of manure treatment *(Husfeldt et al., 2012; Zhang et al., 2009; Zhou et al., 2023)*. In addition, solid-liquid separation has great potential to contribute to the realization of the “two-carbon” goal. Studies have shown that the use of solid-liquid separation can reduce greenhouse gas emissions from farms by up to 38% *(Aguirre-Villegas et al., 2014; Aguirre-Villegas et al., 2019)*. However, the solid-liquid separation technology for livestock and poultry manure in China is relatively weak. The inability to achieve high quality and high efficiency solid-liquid separation seriously restricts the subsequent links to carry out, and is the bottleneck of livestock and poultry manure resource utilization *(Hjorth et al., 2011)*.

Currently, livestock and poultry manure solid–liquid separation technologies mainly include three types: centrifugal, filter-press, and screening. Among them, screw extrusion separation technology, which features low energy consumption and lower investment costs, is the most widely used *(Anlauf, 2007)*. However, there is a trade-off between processing efficiency and the water content of the extrudate, improving one performance indicator often leads to a decline in the other. Therefore, the screw extrusion solid-liquid separator still requires optimization, with the goal of achieving the best possible balance between these two performance parameters.

Currently, the separation technology of solid-liquid mixtures of livestock and poultry manure is receiving attention and research applications from many scholars both in China and abroad *(Jiang et al., 2016; Luo et al., 2020)*. The study done by *Burton et al. (*2007*)* emphasized the key role of solid-liquid separation in livestock and poultry manure treatment, pointing out that the mechanical separation means can effectively remove about 80% of the dry matter components of manure. *Moller et al (2000)*, on the other hand, revealed that the dry matter concentration (TS) of raw materials has a significant effect on the treatment capacity of screw solid-liquid separation equipment. Concentration (TS) has a significant effect on the processing capacity of screw solid-liquid separation equipment. *Shi Huixian et al. (2014)* explored the relationship between TS and apparent viscosity of swine manure and found that swine manure exhibited pseudoplastic fluid properties and followed a power rate equation.

Popovic et al., (2014) investigated the effect of additives, such as biochar, on the separation performance of a screw extruder, and the results showed that the addition of biochar to swine manure could improve the separation efficiency by 2% to 3%. *Apachanov et al. (2016)* modeled the material movement inside the screw extruder, and pointed out that the “dead zone” of the material inside the screw and the rotation around the center of the axis are the main factors leading to the decrease of separation efficiency and the increase of energy consumption.

Guan Zhengjun et al. (2011) optimized the process parameters of a screw press separator by taking the TS of separated solids as the main evaluation index. *Shen Jiangtao et al. (2014)* designed a broken screw extrusion separator. *Zhao Weisong et al. (2017)* and *Zhu et al., (2017)* optimized the design of a broken-tooth screw extrusion separator and carried out structural optimization and simulation studies to achieve better progress.

The influence of many factors on separator performance has been explored in previous studies *(Hjorth et al., 2011; Husfeldt et al., 2012).* Examples include material properties of the manure, structural parameters of the screw (e.g., pitch, screw length, interrupted distance, etc.), and kinematic parameters (e.g., screw rotation speed) *(Zhao et al., 2017)*. However, there are more influencing factors on the operation of screw extrusion separator, and the influence law of the factors and the interaction of the factors on the performance of solid-liquid separation still needs to be studied in depth. In particular, the structural parameters at the solid outlet, the lack of research on the effects of extrudate water content and solid extraction rate, restricts the further optimization of the design of the screw extrusion separator.

For this reason, this study designs a screw separator and investigates the effects of extender length, screw rotation speed, and counterweight mass on the device’s dewatering performance. It analyzes the influence of each factor on the evaluation indices and determines the optimal parameter combination. The goal is to provide theoretical support for the design and optimization of screw extrusion dewatering machines.

MATERIALS AND METHODS

Test materials

The cow manure used in the experiment was from a dairy farm in Haimen City, Jiangsu Province, and the TS of the cow manure was 10.11% at the time of the experiment. The experiment was conducted in August 2022.

Test equipment

Self-developed livestock and poultry manure screw extrusion dewatering device (Nanjing Agricultural Mechanization Research Institute of the Ministry of Agriculture and Rural Development), SKFG-01 dryer electric constant temperature blower drying box (Shanghai Jiecheng Experimental Instrument Co., Ltd.), SAMPO DT2234A tachymeter (Shenzhen Xinbao Science and Technology Instrument Research and Development Center), NL50-8 sewage slurry pump (Shanghai Sunshine Pump Manufacturing Co., Ltd.), QJB3 /8 sludge mixer (Jiangsu Ru Ke Environmental Protection Equipment Co., Ltd.), SECURA612-1CN electronic balance (Suzhou Sainz Instruments Co., Ltd.).

Machine structure and working principle

Livestock and poultry manure screw separator mainly consists of three-phase motor, reducer, screen, screw, extender, head and other parts, of which the screw is one of the key components of the extrusion separator, used to complete the process of conveying materials, extrusion dewatering and discharging, etc. Self-designed screw is divided into the feeding section, extruding section, discharging section, and adopts a double-screw design. The outer diameter of the screw is 260 mm and the diameter of the screw shaft is 120 mm.

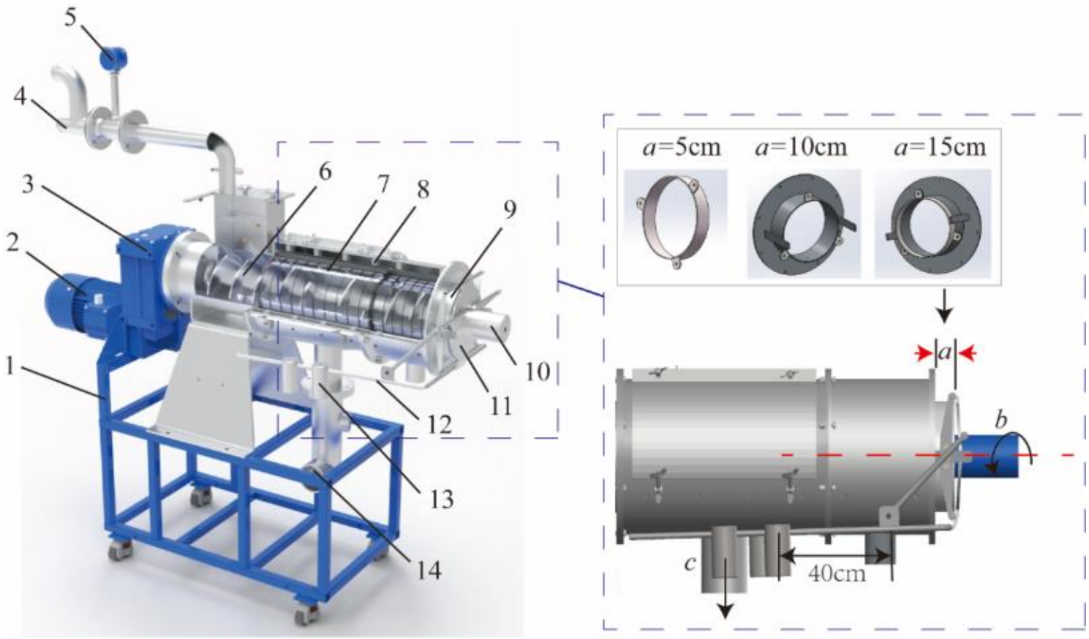

Fig. 1 Structural sketch and parameter adjustment method of screw separator

1. Frame; 2. Motor; 3. Reducer; 4. Inlet; 5. Flow meter; 6. Screw; 7. Screen; 8. Screen retainer; 9. Extender; 10. Rotating shaft; 11. Solid outlet baffle; 12. Pressure plate; 13. Counterweight; 14. Liquid outlet

Test method

The water content of extrudate characterizes the wet and dry separation effect of manure, which has a significant impact on the subsequent utilization, and is an index of the performance of wet and dry separator. Separation efficiency reflects the volume of manure that can be processed by the machine per unit of time, and is the main basis for the matching relationship between the scale of farming and the number of machines. Therefore, the water content of the extrudate and the processing efficiency were selected as the objective function. The results of existing studies have shown that the rotational speed of the screw and the outlet resistance are important factors affecting the water content of the extrudate and the separation efficiency. The previous pre-test study shows that the extender length has a greater impact on the wet and dry separation performance: when the extender is shorter, the discharge speed is faster, but the water content is high. When the extender is longer, the discharge speed is slower, but the water content is lower. Therefore, based on the existing results and pre-test results, the initial ranges of the three influencing factors, screw rotation speed, outlet resistance and extender length, were determined, where the outlet resistance is usually measured by the counterweight mass. A three-factor, three-level response surface test design methodology was used with 17 sets of tests, which included five zeros. Based on the Box-Behnken design principle, the response surface test was carried out on the three factors of screw rotation speed, counterweight mass and extender length with extrudate water content and separation efficiency as the evaluation indices, and the test factors and levels are shown in Table 1.

Table 1

Factors and levels of response surface test

Level	Extender Length *a* [mm]	Screw rotation speed *b* [$r \cdot min^{-1}$]	Counterweight mass *c* [kg]
-1	5	25	20
0	10	40	30
1	15	55	40

The indices were determined by the following methods: separation efficiency was calculated by the volume of cow dung treated per unit time, and water content was calculated by the standard drying method. Before the test, the cow dung was placed in the liquid storage tank, the stirring pump worked continuously to ensure good uniformity of the material in the tank, the timing started when the machine was running stably, and stopped after 30 min of operation, and the separated solids and liquids were collected to be weighed and measured, and the test was repeated three times. Design-Expert 8.0.6 software was used to perform quadratic polynomial regression analysis on the test data for separation efficiency and water content of the extrudate, and response surface analysis was used to study the correlation and interaction effects of the factors.

RESULTS AND ANALYSIS

Test results

The test results and 2 response values are shown in Table 2. In the test, the livestock and poultry manure screw extrusion dewatering device can successfully complete the extrusion dewatering operation, and within the range of the selected parameters, the solids extraction rate varies from 1.78 to 2.63 m^3/h, and the water content of extrudate varies from 53.54% to 74.49%.

Table 2

Experiment design and response values

std	run	Extender length *a*	Screw rotation speed *b*	Counter weight mass *c*	Moisture content of dried fecal solids after separation y_1 [%]	Efficiency of dried manure extraction y_2 [$m^3 \cdot h^{-1}$]
4	1	1	1	0	53.54	2.10
3	2	-1	1	0	72.05	2.60
17	3	0	0	0	68.88	2.40
1	4	-1	-1	0	74.49	2.58
11	5	0	-1	1	67.47	2.11
6	6	1	0	-1	57.27	1.97
5	7	-1	0	-1	73.85	2.30
12	8	0	1	1	63.87	2.34
15	9	0	0	0	68.64	2.30
10	10	0	1	-1	69.01	2.22
8	11	1	0	1	55.09	1.97
13	12	0	0	0	69.72	2.30
9	13	0	-1	-1	69.86	2.11
14	14	0	0	0	65.39	2.32
16	15	0	0	0	68.23	2.33
2	16	1	-1	0	56.57	1.78
7	17	-1	0	1	70.74	2.63

Regression modeling and significance test

According to the sample data in Table 2, multiple regression fitting analysis was carried out using Design-Expert software to establish the quadratic polynomial response surface regression models of y_1 and y_2 on extender length *a*, screw rotation speed *b* and counterweight mass *c* as shown in Eqs. (1) and (2), and the regression equations were subjected to analysis of variance (ANOVA), and the results are shown in Table 3.

$$y_1=68.17-8.58a-1.24b-1.60c-0.15ab+0.23ac-0.69bc-3.66a^2-0.35b^2-0.27c^2 \quad (1)$$

$$y_2=2.33-0.29a+0.09b+0.06c+0.08ab-0.08ac+0.03bc-0.02a^2-0.04b^2-0.09c^2 \quad (2)$$

where, y_1 is moisture content of dried fecal solids after separation, %; y_2 is efficiency of dried manure extraction, $m^3 \cdot h^{-1}$; *a* is extender length; *b* is screw rotation speed; *c* is efficiency of dried manure extraction.

Table 3

Variance analysis

Index	Source	Sum of Squares	df	Mean Square	*F*-value	*P*-value
y_1 [%]	Model	683.05	9	75.89	38.44	< 0.0001**
	a	589.27	1	589.27	298.44	< 0.0001**
	b	12.30	1	12.30	6.23	0.04*
	c	20.54	1	20.54	10.40	0.01*
	ab	0.087	1	0.087	0.04	0.84
	ac	0.22	1	0.216	0.11	0.75
	bc	1.89	1	1.89	0.96	0.36
	a^2	56.47	1	56.47	28.60	0.001**
	b^2	0.51	1	0.51	0.26	0.628
	c^2	0.31	1	0.31	0.16	0.70
	Residual	13.82	7	1.97		
	Lack of Fit	2.96	3	0.99	0.36	0.78
	Pure Error	10.86	4	2.71		
	Cor Total	696.88	16			
y_2 [$m^3 \cdot h^{-1}$]	Model	0.84	9	0.09	26.87	0.0001**
	a	0.66	1	0.66	188.64	2.56E-06**
	b	0.06	1	0.06	16.63	0.005**
	c	0.03	1	0.03	7.28	0.030*
	ab	0.02	1	0.02	6.47	0.038*
	ac	0.03	1	0.03	7.83	0.027*
	bc	0.003	1	0.004	1.04	0.343
	a^2	0.002	1	0.002	0.55	0.484
	b^2	0.008	1	0.008	2.32	0.172
	c^2	0.035	1	0.035	10.09	0.016*
	Residual	0.024	7	0.003		
	Lack of Fit	0.018	3	0.006	3.44	0.132
	Pure Error	0.007	4	0.002		
	Cor Total	0.865	16			

*Note: P＜0.01 (highly significant,**); P＜0.05 (significant, *).*

Based on the results of the analysis in Table 3, it can be seen that the *P*-values of the regression equations y_1 and y_2 are less than 0.01, which indicates that the response surface model is highly significant. The *P*-value of the misfit term of the model is greater than 0.05 (y_1=0.784, y_2=0.132), and the non-significant misfit term indicates that the model matches the data to a high degree. y_1 and y_2's coefficient of determination, R^2, are 0.98 and 0.97, respectively, which indicates that the two models can explain more than 97% of the evaluation indices. Based on the above results, it can be seen that the model can adequately describe the 2 response variables of extrudate water content and treatment efficiency, and the prediction of the response surface model is accurate and can be used to optimize the parameters of the screw.

In order to optimize the regression equation, the independent variables that have less influence on the response variables need to be eliminated, and the influence of each parameter on the regression model equation can be reflected by the *P* value.

In the extrudate water content model y_1, the effects of 2 items, a and a^2, were highly significant (P < 0.01); the effects of 2 items, b and c, were significant (P < 0.05); and the effects of the remaining 5 items, ab, ac, bc, b^2 and c^2, were not significant (P > 0.05).

In the dry matter extraction rate model y_2, the effects of a and b^2 terms were highly significant (P < 0.01); c, ab, ac, and c^2, 4 terms were significant (P < 0.05); and the remaining bc, a^2, and b^2 3 terms were insignificant (P > 0.05).

The optimized model was obtained after removing the insignificant terms, as shown in Eq.(3) and Eq.(4).

The significance test *P*-values of the optimized models y_1 and y_2 are both less than 0.01 respectively, indicating that the models are highly significant. None of the misfit terms are significant, indicating a good match between the data and the model. The optimized model is more concise and precise, and can be used for prediction and analysis of actual production.

$$y_1=67.9-8.58a-1.24b-1.60c-3.7a^2 \quad (3)$$

$$y_2=2.3-0.2862a+0.085b+0.0562c+0.075ab-0.0825ac-0.0949c^2 \quad (4)$$

Effect analysis of the influence of each factor on the response value

The influence magnitude of each factor on the evaluation index was determined through the analysis of variance (ANOVA) results in Table 3. The influence of each factor on the water content of the extrudate is in the following order from the largest to the smallest: $a > c > b$. It indicates that among the three factors, the extender length (a) has the greatest influence on the water content of the extrudate, the counterweight mass are the second largest (c), and the screw rotational speed (b) has the smallest influence. This finding is in line with the previous findings that the effects of b and c on y_1 are consistent with the findings of literature (*Zhao et al., 2017*). It was also found that the effect of extender length (a) on y_1 was highly significant over the effect of factors b and c. This finding was missing in the previous study.

The effect of each factor on solids extraction rate was ranked in descending order: $a > b > c$. This indicates that among the three factors, extender length (a) had the greatest effect on solids extraction rate, followed by screw rotational speed (b), and counterweight mass (c) had the least effect. This conclusion indicates that the extender length is an important factor affecting the operational performance of the screw extruder separator, and is the key influence factor of the two evaluation indices of extrudate water content and solids extraction rate. The length of the extender can be adjusted to seek a balance between the two indices of extrudate water content and solids extraction rate to maximize the performance of the separator design.

Interaction analysis of influence factors

Response surface analysis was utilized to examine the effects of factors a, b, and c on the 2 response values of extrudate water content and solids extraction rate, with the goal of determining whether there is an optimal combination of factors when extrudate water content is minimized and solids extraction rate is maximized.

The response surface curves of the interacting factors on extrudate water content are shown in Figure 2, with each response surface plot representing the interaction between the other 2 independent variables when one factor is at the center level.

As can be seen in Fig. 2a, y_1 increases with decreasing a, exhibiting a more pronounced change, and y_1 decreases with increasing b, showing a smaller effect.

The shape of the response surface in Fig. 2b is basically the same as that in Fig. 2a, i.e., c decreases and y_1 increases by a small amount.

From Fig. 2c, it can be seen that y_1 increases as either b or c decreases, and the surface change trend is overall flatter.

From Figure 2d, it can be seen that y_2 increases as a decreases, with a larger change, and y_2 increases as b increases.

From Fig.2e, it can be seen that y_2 increases with the decrease of a, and y_2 shows a trend of first increase and then decrease with the increase of c, and there is a maximum value.

Similarly, in Fig. 2f, y_2 shows a trend of change with the increase of c, and there is a maximum value. The change rule of the response surface is consistent with the analysis results in Table 3.

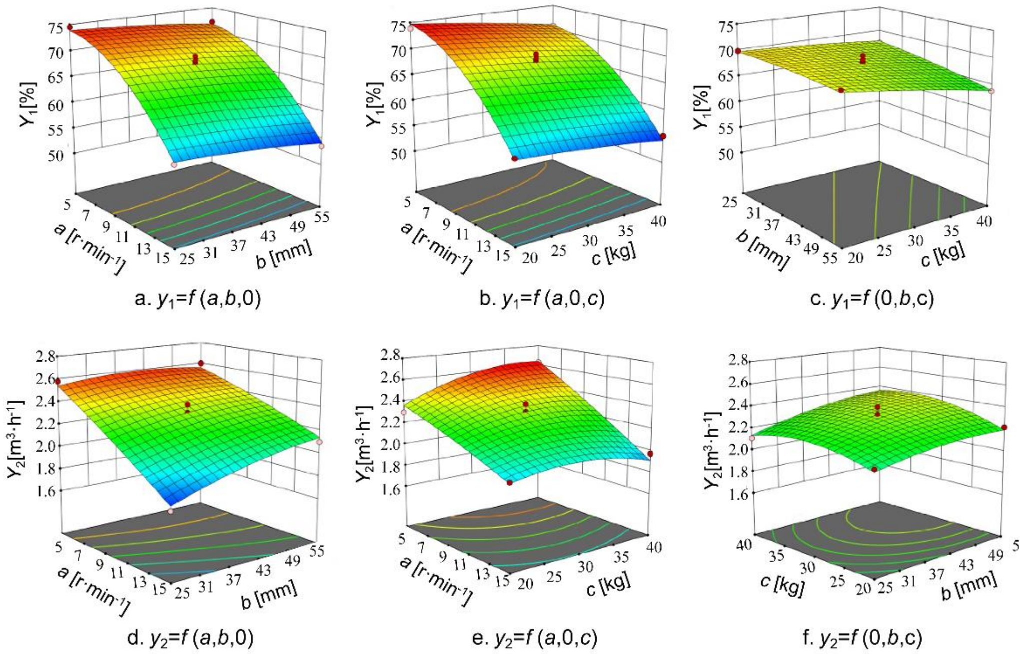

Fig. 2 - Effect of interaction factors on response indicators

Parameter optimization and validation tests

Parameter optimization

In order to realize the optimal operating effect, the solids extraction rate is maximized by ensuring that the water content of the extrudate meets the process requirements for fermentation and other procedures (≤70%). According to the response surface analysis, it can be seen that: to improve the solids extraction rate, it is necessary to reduce the extender length and increase the screw rotation speed. To reduce the water content of extrudate, it is necessary to increase the extender length, increase the screw rotation speed and increase the counterweight mass. The influence of each factor on the water content of the extrudate and the solid extraction rate is more complex, therefore, multi-objective optimization is used to seek the optimal combination of parameters to meet the objectives.

In the livestock and poultry manure fermentation and composting process, the water content of extrudate <70% is more appropriate. In the actual operational requirements, the larger the solids extraction rate is, the higher the efficiency is. Therefore, with y_1 <70% and at the same time y_1 maximum as the objective, Design-Expert software was used to optimize the solution of each parameter. Establish the parameter optimization mathematical model, set the solution objective and constraints as shown in equation (5).

$$\begin{cases} max y_2\left(a,b,c\right) \\ 60\% \le y_1\left(a,b,c\right) \le 70\% \\ s.t.\begin{cases} 5 \le a \le 15 \\ 25 \le b \le 55 \\ 20 \le c \le 40 \end{cases} \end{cases} \tag{5}$$

According to the solution results, one of the optimal parameter combinations is selected: a=10 cm, b=55 r/min, c=34.73 kg, at this time, the theoretical value of extrudate water content y_1=65.44%, and the theoretical value of solids extraction rate y_2=2.39 m³/h.

Experimental verification

In order to verify the accuracy of the obtained model prediction results, a validation test was carried out. Five replicate tests were conducted with parameter combinations (a=10 cm, b=55 r/min, c=34.73 kg) and the results are shown in Table 4.

Table 4

Validation test results

No.	y_1 [%]	y_2 [$m^3 \cdot h^{-1}$]
1	69.72	1.89
2	68.26	2.51
3	67.78	2.36
4	62.93	1.99
5	69.88	2.06
Average	67.71	2.16
Relative error/%	2.82	0.34

In the validation test, the mean value of water content of the extrudate was 67.71% with a relative error of 3.3% from the theoretical prediction (65.44%). The mean value of solids extraction rate was 2.10 m³/h, and the relative error to the theoretical prediction (2.39 m³/h) was 9.6%. The measured and theoretically predicted values of the two evaluation indices are <10%, indicating that the model is reliable and can be used for parameter optimization. The test site is shown in Figure 3.

Fig. 3 - Tests Scenarios

CONCLUSION AND DISCUSSION

The Box-Behnken central combination test method was used to study the influence law of three factors (extender length, screw rotation speed, counterweight mass) on two evaluation indices (water content of extrudate, solids extraction rate), and the optimization model of the influence factors and evaluation indices was established. The model and optimization results were verified through tests, and the results showed that the model and optimization results were accurate and reliable.

The test results show that the order of significance of the influence of each factor on the water content of extrudate is extender length (*a*), counterweight mass (*c*), screw rotation speed (*b*) in descending order of significance. The order of significance of the effect of each factor on solids extraction rate was in descending order of significance: extender length (*a*), screw rotation speed (*b*), counterweight mass (*c*). In this study, extender length was found to be one of the most critical factors affecting the working performance of the screw extruder separator. This factor has a highly significant effect on both extrudate water content and solids extraction rate. As the extender length increases, the water content of the extrudate decreases, but the solids extraction efficiency also declines. In order to obtain the optimal parameter combinations, a multi-objective optimization function was established, and one of the optimal parameter combinations was obtained as: *a*=10 cm, *b*=55 r/min, *c*=34.73 kg. Under the optimal parameter combinations, the mean value of extrudate water content was 67.71% and the mean value of solids extraction rate was 2.10 m³/h in the validation test.

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