ANALYSIS AND DESIGN OF SOLID-LIQUID MIXED FERTILIZER DEVICE FOR ORGANIC FERTILIZER ON SOLID-LIQUID TWO-PHASE FLOW

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基于固液两相流的有机肥固液混合施肥装置分析与设计

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ABSTRACT

Organic fertilizer applicator currently has poor versatility toward different properties. A solid-liquid mixed fertilizer device is designed based on the numerical simulation method of solid-liquid two-phase flow. Based on the parameters analysis and viscosity measurement of different organic fertilizer particles, the ribbon-screw type agitator was selected as the basic structure. Using Box-Behnken, three test factors including agitator speed, the mixture ratio of fertilizer and water, agitator height were determined, the agitator was optimized with the test evaluation indexes, the density variation coefficient, and agitator shaft power on 10 mixing planes in the agitator. The result showed that the rotating speed was 80 r/min, the mixing ratio of fertilizer and water was 1.2, and the agitator height was 700 mm, the working parameter combination is optimal. A coarse particle solid-liquid two-phase flow model of the fertilizer discharge pump was established, to obtain the external characteristic curve of the fertilizer pump and analyse the influence of different mixing ratios of fertilizer and rotation speed on the fertilizer pump. In order to prevent the separation of fertilizer and water and achieve better effect, 1140 r/min was comprehensively determined as the working speed of the fertilizer pump. The strength of the agitator meets the working requirements. The solid-liquid deep fertilizer device text bench for organic fertilizer was set up under the optimal working parameters, the result shows that the research results can provide a reference for the design of organic fertilizer solid-liquid mixing fertilizer applicator.

摘要

针对目前有机肥施肥机对不同形态有机肥通用性差，基于固液两相流数值模拟方法，分析并设计一种有机肥固液混合施肥装置。根据多种有机肥颗粒参数分析和黏度测定，通过六种搅拌器固液两相流试验筛选螺带-螺杆式搅拌器型为搅拌装置基本结构。采用 Box-Behnken 试验设计方法进行搅拌器优化，以搅拌器转速、肥水混合比、搅拌器高度 3 个试验因素，肥料桶内 10 个混合平面的密度变异系数和搅拌器轴功率为试验评价指标，转速80r/min、肥水混合比1.2、搅拌器高度700mm 时效果最优，10 个截面的平均密度为713.16kg/m3，轴功率为24.07kW，变异系数为4.32%。建立排肥泵粗颗粒固液两相流模型，获取排肥泵外特性曲线及排肥泵泵肥影响因素，选取 1140r/min 为排肥泵工作转速。在最优工作参数下搭建有机肥固液混合施肥装置试验台架，台架试验结果表明研究结果可为有机肥固液混合施肥机设计提供参考。

INTRODUCTION

The large amount of fertilizer in agricultural planting increases the risk of environmental pollution (*Han Tang et al, 2019; Hossain Md Zahangir et al, 2021*). The utilization of organic wastes such as livestock manure can greatly reduce the use of chemical fertilizer. Fertilization technology has an important impact on the yield and quality of crops. Reducing fertilizer and increasing efficiency has become an urgent need for sustainable agricultural development (*Rodrigues L.A.T. et al, 2021*). Studies have shown that by applying organic fertilizer instead of chemical fertilizer (*An Siyu et al, 2019*), 70 % of the regions can achieve the goal of chemical fertilizer reduction and reduce the non-point source pollution of nitrogen and phosphorus fertilizers (*Geng Xiuhua et al, 2020; Geng Wei et al, 2013; Sagues William J et al, 2020; Xiaoyong Liu et al, 2018*).

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The development of organic fertilizer fertilization machinery is also an important means to promote the application of organic fertilizer (*Quiroz et al, 2019*). At present, the application of organic fertilizer mainly stays in the stage of artificial spreading, and the mature organic fertilizer fertilization machinery types are less, mainly concentrated in the spreading machine of solid organic fertilizer and scraper furrow fertilization machine (*Li Jie et al, 2013*). The volume of solid organic fertilizer spreader is large, which can also cause environmental pollution (*Chen Genqiang et al, 2019; Jie Hu et al, 2018; Zhou Yang et al, 2020*); Scraper furrow fertilization machine cannot perform accurately quantitative fertilization according to depth, nor can organic fertilizer be applied to the root part of crops, so fertilizer efficiency is relatively low (*Li Jie et al, 2013*).

There are many kinds of organic fertilizers, which can be divided into solid fertilizers and liquid fertilizers according to the form (*Liu Cailing et al, 2017; Zhou Wenqi et al, 2020; Kang Jianming et al, 2017; Chen Xiongfei et al, 2015; Zeng Shan et al,2020*). Solid fertilizers also include farm compost, stable manure, commercial granular organic fertilizer, and powdery organic fertilizers (*Wang Jinwu et al, 2018; Xu Binxing et al, 2017; Fu Yuchao et al, 2017*). Because farm compost, stable manure, and so on are easy to plug the hole of hole fertilizer applicator, the existing hole fertilizer applicator can only apply commercial granular organic fertilizers (*Bai Youlu et al, 2016*). Liquid organic fertilizer applicator spreads the liquid organic fertilizer directly into the soil or it is applied with drip irrigation, but the production cost is high, fertilization machinery layout is complex, it cannot directly apply manure, crop straw, and other organic fertilizer sources (*Liao Junjie et al, 2021; Chiharu Tokoro et al, 2021*).

According to the fertilization characteristics and technical requirements of organic fertilizer, aiming at the poor universality of organic fertilizer for different physical properties at present, based on the numerical simulation method of solid-liquid two-phase flow, this paper explored the fertilization method of solid-liquid mixed organic fertilizer, studied the effects of different solid-liquid mixing ratios, agitator forms and stirring speeds on the mixing effect, optimized the working parameters of agitator and fertilizer pump, and carried out the bench test, to provide a reference for the design of solid-liquid mixed organic fertilizer applicator.

MATERIAL AND METHOD

Determination of Organic Fertilizer Parameters

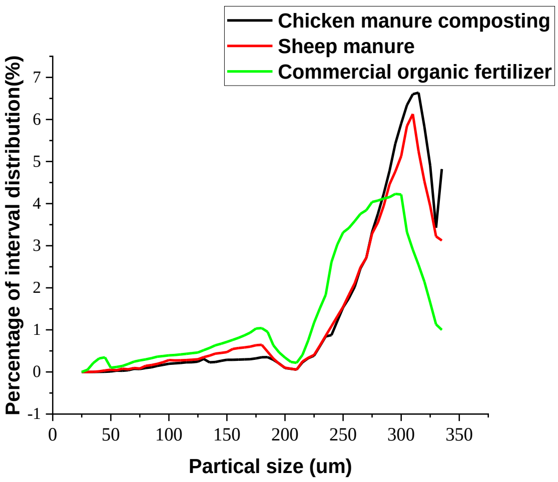


Fig. 1 - Particle size distribution of three kinds of organic fertilizers

Organic fertilizer has a wide variety and complex composition (*Himmelsbach W. et al, 2021*). The mixture of organic fertilizer and water is generally considered a non-Newtonian fluid. According to the design of the fertilizer blender and the needs of flow field analysis, three kinds of organic fertilizers, including chicken manure compost, sheep manure, and commercial powdery organic fertilizer, were selected for crops (*Christwardana M. et al, 2020*). The particle size of organic fertilizer was measured by a laser particle size analyzer (*Foukrach Mohammed et al, 2020*). The measurement results are shown in Fig.1. The particle size of organic fertilizer was mainly distributed between 150-350 um, accounting for more than 85%, and the cumulative proportion between 275-325 um was 48.33%, taking chicken manure composting as an example. The particle size distribution of chicken manure compost was larger than that of sheep manure and commercial powder organic fertilizer, and the particle size of commercial powder organic fertilizer was the smallest and the distribution was the most uniform. The average volume diameter, average area diameter, and average length diameter of chicken manure compost were higher than those of other fertilizers.

According to the needs of practical application and numerical simulation, the viscosity of three kinds of organic fertilizers at different mixing ratios of fertilizer and water mass and stirring speeds was measured by a rotary viscometer. The measurement results are shown in Table 1. The viscosity of organic fertilizer increases with the increase of fertilizer-water ratio; with the increase of stirring speed, the viscosity decreases gradually. Among the three organic fertilizers, chicken manure compost had a wider range of viscosity distribution and the highest viscosity. The viscosity of sheep manure is the lowest.

Table 1

Results of viscosity measurement of organic fertilizer

Mixed ratio of fertilizer and water	Viscometer speed (r/min)	Commercial powder viscosity (Pa·s)	Viscosity of chicken manure compost (Pa·s)	Viscosity of sheep manure (Pa·s)
1:1	40	2.50	0.74	1.21
1:1	60	1.02	0.35	0.66
1:1	80	0.59	0.16	0.31
1.1:1	40	12.55	7.25	3.20
1.1:1	60	3.17	3.28	1.65
1.1:1	80	1.07	1.85	0.70
1.2:1	40	19.67	22.37	4.47
1.2:1	60	7.93	7.16	1.93
1.2:1	80	3.49	4.99	1.10

Design of solid-liquid fertilizer tank

The fertilizer tank mainly includes a tank and other structures installed in the tank. In order to achieve the best mixing effect, the mixer and fertilizer tank need to be well matched. Relevant parameters of fertilizer tanks are designed according to relevant standards and pressure vessel design manuals. The relationship between the diameter of fertilizer tank and the parameters is Eq. (1).

Due to fact that the mixing of materials in the fertilizer tank belongs to the mixing of liquid-solid materials, the length-diameter ratio H/D_i is 1-1.3, the material reaction is gentle in the process of organic fertilizer mixing, there is no boiling state, the foam is less, and the material coefficient η_i is 0.8-0.85. Through calculation and analysis, the fertilizer tank structure is designed as V_N = 0.4 m^3, D_i = 0.8 m, H = 0.8 m, and the flat bottom removable flat cover fertilizer tank is selected. The solid-liquid mixing medium of organic fertilizer has high viscosity. The baffle set in the fertilizer tank will hinder the mixing of organic fertilizer, and the diversion effect of the draft-tube is not obvious, so the fertilizer tank is not set with baffle and draft-tube.

$$H = \frac{V - v_q}{\frac{\pi}{4} D_i^2} = \frac{\frac{V_N}{\eta_i} - v_q}{\frac{\pi}{4} D_i^2} \tag{1}$$

where: D_i – is diameter of fertilizer tank, m; η_i - material coefficient; V_N - nominal volume of fertilizer tank, m^3;
V - full volume of fertilizer tank, m^3; v_q - other structural volumes of fertilizer tank, m^3;
H - height of fertilizer tank, m

Type Selection of Solid-liquid Mixer

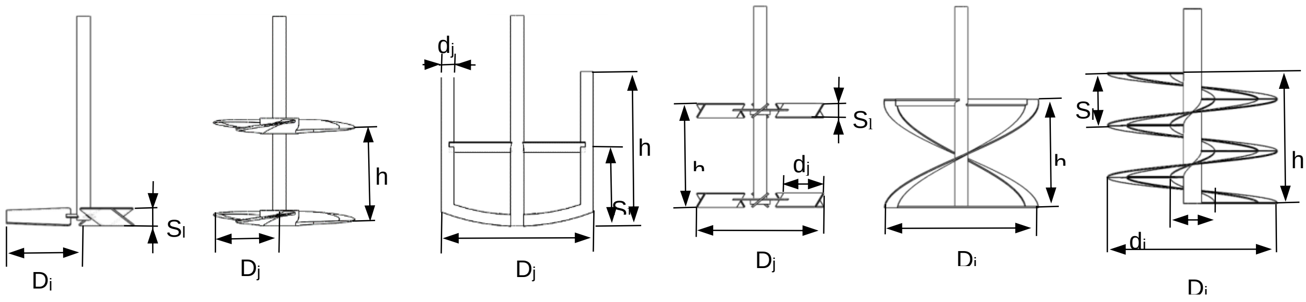
Organic fertilizer is a mixture of water-soluble substances, which contains sand, grass, humus, and other substances insoluble in water. Solid-liquid mixing of organic fertilizer and water involves complex solid-liquid two-phase fluid dynamics. According to the traditional design and calculation method, it is impossible to design a reasonable impeller structure shape and size and to calculate the critical speed and shaft power. Based on the above reasons and the measured viscosity of organic fertilizer, the selected stirrer requires that the organic fertilizer and water-solid-liquid mixture are mixed uniformly after mixing, and there is no large amount of deposition medium at the bottom of the fertilizer tank.

To promote the settlement of low-density grass and reduce the deposition of high-density sand, a vertical stirring device was designed. The working environment of an organic fertilizer mixer is a mixture of solid and liquid. According to the particle parameters of organic fertilizer and the viscosity data of solid-liquid mixture with different mixing ratios, the viscosity range of the mixture is 0.31-22.37 Pa•s. Combined with the determination and analysis of organic fertilizer parameters and the design of stirring device, and referring to the design manual, the medium viscosity of the mixer working environment should be less than 100 Pa•s, and the commonly used speed should be 1-100 r/min.

Table 2

Agitator size parameters

Agitator	D_j (mm)	d_j (mm)	S_l (mm)	h (mm)
Inclined vane	380	—	85	—
Push type	380	—	—	400
Box	760	40	300	500
Folded blade turbine	700	250	80	400
Screw belt type	760	—	—	400
Screw-screw type	760	200	200	500



a) b) c) d) e) f)

a) Oblique blade type; b) Propelling type; c) Box; d) Folded blade turbine; e) Screw belt; f) Screw-screw

Fig. 2 - Agitator type

According to the requirements of solid-liquid mixing, six types of agitators were selected: inclined blade type, propulsion type, frame type, broken blade turbine type, spiral belt type, and spiral belt-screw type. Mixer types, as shown in Fig. 2. The tank height *H* and inner diameter D_i are both 800 mm. Referring to the design manual and combined with the actual size requirements of the mixing drum, the size parameters of each mixer are determined as shown in Table 2. At the rotational speed of 60 r/min, organic fertilizer and water were mixed with solid-liquid according to the mass ratio of 1.1: 1. The stirring effect of the agitator was judged by observing the stirring flow pattern and stirring effect evaluation index of different agitators, and the effective agitator was selected.

Establishment of Solid - liquid Mixing Mechanism Model

The particle size of chicken manure compost in organic fertilizer is wider than that of sheep manure and commercial powdery organic fertilizer, and the particle size is large and the viscosity is the highest. The physical parameters of chicken manure compost are selected as the solid particle modeling parameters. The liquid is clear water, and the mixed fertilizer mixer is mainly used for solid-liquid two-phase mixing. In the process of solid suspension, there is a minimum stirring speed that makes the solid suspension, which is called the critical stirring speed of solid suspension. When the solid is completely suspended, the critical speed has the lowest energy loss. The critical stirring speed is calculated by the formula of critical stirring speed, and the speed range of the mixer is determined. The calculation formula of critical stirring speed is Eq. (2).

$$N_c = K D_i^{-2/3} d_p^{1/3} \left(\frac{\Delta\rho}{\rho}\right)^{2/3} \left(\frac{\mu}{\rho}\right)^{-1/9} \left(\frac{V_s}{V_p}\right)^{-0.7} \tag{2}$$

where:

K - is stirring coefficient. The mixing device coefficient is 187-263, which is related to the shape of the fertilizer drum and the form and size of the agitator;

D_i - inner diameter;

d_p - solid particle diameter, mm; $\Delta\rho$ - the density difference between solid particles and liquids, g/m^3;

ρ - Fluid density, g/m^3; μ - Fluid Viscosity, Pa•s;

V_p - solid true volume, m^3; V_s - apparent volume of solids, m^3

The stirrer speed range is set as 1-100r/min, d_p is 0.3mm, and after drying the particle density is 580 kg/m^3. According to the structural design of the stirring device and the viscosity data measured in Table 1, the liquid density and viscosity under different rotational speeds and fertilizer-water mixing ratios were determined to calculate the critical stirring speed, respectively. In the numerical simulation, the rotational speeds of the agitator were set as 40 r/min, 60 r/min, and 80 r/min. The volume and volume fraction of water and fertilizer were calculated according to the mass ratios of organic fertilizer and water 1: 1, 1.1: 1 and 1.2: 1.

The model adopts the sliding mesh method. The cylindrical shape of the rotating domain and the static domain is established, and then the static domain and the rotating domain are formed by the Boolean operation to improve the accuracy of numerical simulation. The mesh module is selected for meshing in the model. The mesh correlation coefficient is set to 100, and the density is fine. Ten layers of expansion layer are set in the rotating domain, and the tetrahedral mesh is used for the mesh. The obtained mesh has good quality. RNG k-ε model is used for numerical simulation of flow field

According to the solid-liquid mixing process and the designed rotational speed of the test, the boundary conditions in the fluid simulation module were added, and the wall around the fertilizer bucket was set, and the rest surfaces were automatically generated by the software. The gravity direction y was set as the negative direction, and the rotational speeds of the agitator were 40 r/min, 60 r/min, and 80 r/min, respectively. Organic fertilizer belongs to small particle flow, and solid-liquid mixing adopts the Euler-Euler multiphase flow model, and the two-phase mixture model is set. The first phase is water, and the second phase is organic fertilizer. The relevant parameters of organic fertilizer were obtained through the parameter analysis of organic fertilizer particles and the viscosity test. The turbulence model was RNG k-ε turbulence model, and the constant values of the RNG k-ε model are shown in Table 3. The initialization state parameter settings are shown in Table 4.

Table 3

RNG k-ε model constant

σ_k	σ_ε	$C_{\varepsilon 1}$	$C_{\varepsilon 2}$	C_μ	η_0
0.8311	0.8311	1.44	1.92	0.09	4.36

Table 4

Parameter setting

Parameter	Numerical value
Water density (kg/m^3)	1000
Particle diameter of organic fertilizer (mm)	0.3
Density of organic fertilizer (kg/m^3)	580
Volume fraction of second phase (%)	63.24、65.43、67.37
Rotating shaft speed (r/min)	40、60、80

Mixer screening

Evaluation of the agitator is made mainly from two aspects: mixing effect and energy consumption. There are many ways to determine the mixing effect. The standard deviation of average density is commonly used for non-Newtonian fluid, that is, the standard deviation is calculated by the average density of the uniform section in the vertical direction of the flow field analysis results. The smaller the standard deviation is, the smaller the density difference between the representative sections is, and the better the mixing effect of the mixer is. Because this experiment involves different fertilizer-water mixing ratio test, the density of different test groups is different; in order to eliminate the influence of different densities on the standard deviation measurement scale and dimension of average density, the coefficient of variation is used as the evaluation index of stirring effect. Mixer shaft power is the evaluation index of energy consumption.

The average density of 10 cross-sections of the flow field analysis results was uniformly selected to calculate the standard deviation, and the average density of the whole mixture above the standard deviation ratio was used as the variation coefficient. The greater the coefficient of variation, the better the mixing effect. Select ten sections from bottom to top of mixing zone. The section selection diagram is shown in Fig. 3.

The average density of each section is ρ_i, i=(1,2 10) , the average density is:

$$D_j = \frac{1}{10}\left\{\sum_{i=1}(\rho_i - \bar{\rho})^2\right\}, i = 1,2\cdots 10, j = 1,2\cdots 6 \tag{3}$$

Standard deviation:

$$\sigma_j = \sqrt{D_j}, j = 1,2\cdots 6 \tag{4}$$

Coefficient of variation:

$$C \cdot V_j = \frac{\sigma_j}{D_j} \times 100\%, j = 1, 2 \cdots 6 \tag{5}$$

In equations (3), (4), (5): *i* – is the corresponding 10 section numbers; *j* - six corresponding mixers.

The torque in the simulation results of flow field analysis is extracted, because the torque and power are positively correlated, and the shaft power of the stirrer is calculated by combining the rotational speed of the stirrer fan blade as the evaluation index of energy consumption. The smaller the shaft power is, the less energy consumption is. The calculation equation of shaft power is:

$$P_j = \frac{M_j \times n}{9550}, \quad j = 1, 2 \cdots 6 \tag{6}$$

In equation (6): *M* – is the mixer torque, N•m; *n* - agitator speed, r/min; P_j - mixer shaft power, kW.

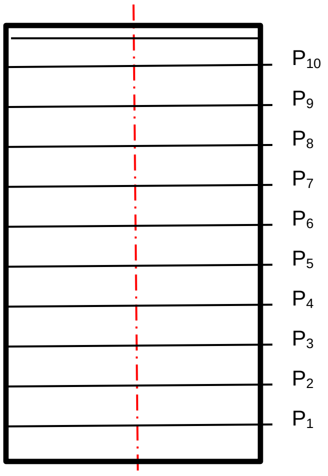


Fig. 3 - Schematic diagram of 10 sections

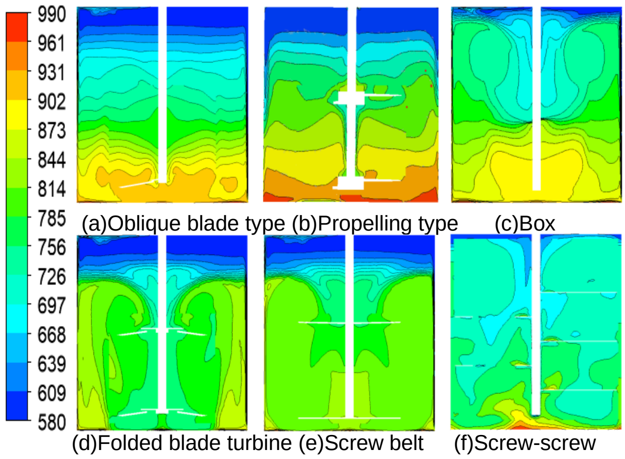


Fig. 4 - Cloud chart of volume concentration distribution in the middle section

According to the design of six kinds of stirrers, the simulation test was carried out to obtain the concentration distribution of solid-liquid mixture after mixing in the mixing drum, and the concentration distribution in the middle section of different stirrers was selected. The test results are shown in Fig. 4. By comparison, it is found that the mixing effect of inclined-leaf mixer and push mixer is poor, and organic fertilizer is still more floating on the surface of the water. The Frame mixer has good laminar mixing at the cross plate, but there is a blind mixing zone at the bottom of the blade, and the effect is not ideal. Blade turbine and spiral belt obtain similar concentration mixing form, with a certain upper and lower circulation capacity, but the effect in the upper and near the wall area of the mixing drum is poor; Screw belt-screw type has good upper and lower circulation ability and can realize the mixing uniformity of full stirred tank.

Ten cross sections (P_1 (Z = 0), P_2 (Z = 85), P_3 (Z = 175), P_4 (Z = 265), P_5 (Z = 355), P_6 (Z = 445), P_7 (Z = 535), P_8 (Z = 625), P_9 (Z = 715), and P_{10} (Z = 800)) from the bottom of the tank were taken as shown in Fig.5. The volume concentration distribution and the variation coefficient of average density on the ten sections were used as the evaluation indexes of mixing effect.

At the speed of 60 r/min and fertilizer-water mixing ratio of 1.1: 1, as shown in Fig. 6, the concentration and density of 10 sections of different stirrers increased gradually from top to bottom. Among them, the density difference between the different sections of the propulsion type is the most obvious, and the difference between the upper and lower ten sections of the screw belt screw type is the smallest, which shows that the mixing uniformity of the ten sections is the best.

According to Eq. (3) to Eq. (5), the coefficient of variation of six mixers was calculated. The coefficient of variation of inclined blade type, propulsion type, frame type, broken blade turbine type, screw belt type and screw belt-screw type were 0.85 %, 0.07 %, 1.07 %, 1.09 %, 1.13 % and 1.87 %, respectively. The propulsion minimum indicates the worst mixing uniformity; The coefficient of variation of the belt-screw agitator was 1.87 %, which was the largest among the six agitators, indicating that the belt-screw agitator had the best mixing uniformity.

Making the comprehensive comparison of the volume concentration distribution program of the middle section, the volume concentration distribution program of the ten sections, and the average density variation analysis of the ten sections of the six mixers, the screw belt-screw mixer structure was determined as the mixing device of the organic fertilizer solid-liquid mixed fertilizer machine in the hilly orchard. The height of the mixer is 500 mm, 600 mm, 700 mm according to the height of the fertilizer tank.

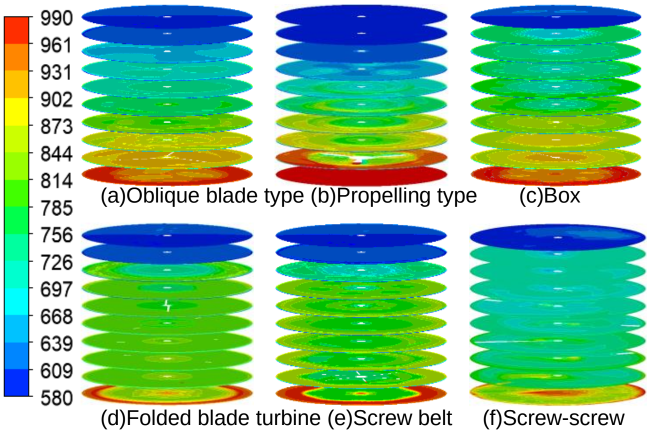


Fig. 5 - Cloud chart of volume concentration distribution on ten sections

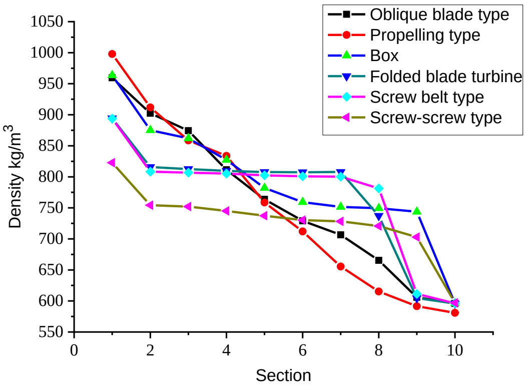


Fig. 6 - Average density distribution on ten sections

Analysis on influencing factors of fertilizer mixing effect of agitator

Based on the fact that there are many structural factors affecting the mixing of agitators, the Box-Behnken design method was adopted. During the experiment, the main factors affecting the stirring effect are the following three: stirrer speed (r/min), fertilizer-water mixing ratio, stirrer height (mm). The stirrer is mainly evaluated from two aspects of stirring effect and energy consumption. The coefficient of variation was used as the evaluation index of the stirring effect. The greater the coefficient of variation, the higher the mixing uniformity, the better the stirring effect. Mixer shaft power is the evaluation index of energy consumption. The torque in the simulation results of flow field analysis was extracted because the torque and power were positively correlated. The power of the agitator shaft was calculated by combining the rotational speed of the agitator as the evaluation index of energy consumption. The smaller the shaft power is, the less energy consumption is. The level and coding of different factors are shown in Table 5.

Table 5

Test factors and codes

Factors	Level		
	-1(Low)	**0(Middle)**	**1(High)**
Stirrer speed (r/min)	40	60	80
Fertilizer-water mixing ratio	1	1.1	1.2
Stirrer height (mm)	500	600	700

Table 6

Test design and results

Test serial number	Stirrer speed (r/min)	Fertilizer-water mixing ratio	Stirrer height (mm)	Coefficient of Variation *C·V* (%)	Shaft power *P*(kW)
1	-1	-1	0	2.19	30.25
2	0	0	0	1.74	7.6
3	1	0	1	3.83	23.35
4	1	-1	0	2.48	43.44
5	0	0	0	1.74	7.6
6	0	1	1	3.25	14.54
7	-1	1	0	2.47	11.45
8	0	1	-1	2.07	6.53
9	1	0	-1	2.54	78.27
10	0	-1	1	2.1	8.73
11	-1	0	-1	2.34	3.74
12	0	0	0	1.74	7.6
13	0	0	0	1.74	7.6
14	0	0	0	1.74	7.6
15	-1	0	1	2.8	7.28

16	1	1	0	2.87	64.65
17	0	-1	-1	1.87	6.17

According to the Box-Behnken experimental principle, the experimental design and results are shown in Table 6. The regression models of stirrer speed, fertilizer-water mixing ratio, and stirrer height on the coefficient of variation and shaft power were established by Design-Expert 11.0 software. The results were shown in Table 7. Fitting model analysis using statistical analysis software to determine the coefficient of variation and shaft power fitting equation, such as Eq. (7) and Eq. (8).

$$C\cdot V=1.74+0.24x_1+0.2525x_2+0.395x_3+0.0275x_1x_2+0.2075x_1x_3+0.2375x_2x_3+0.6587x_1^2+0.1037x_2^2+0.4788x_3^2 \quad (7)$$

$$P=7.6+19.62x_1+1.07x_2-5.1x_3+10x_1x_2-14.62x_1x_3+1.36x_2x_3+24.51x_1^2+5.34x_2^2-3.95x_3^2 \quad (8)$$

Table 7

Variance analysis of regression equation

Evaluating indicator	Source	Sum of Squares	df	Mean Square	f-value	p-value	Significance
Coefficient of Variation $C\cdot V/\%$	**Model**	5.68	9	0.6309	40.63	< 0.0001	**
	x_1	0.4608	1	0.4608	29.67	0.0010	**
	x_2	0.5101	1	0.5101	32.85	0.0007	**
	x_3	1.25	1	1.25	80.38	< 0.0001	**
	x_1^2	1.83	1	1.83	117.66	< 0.0001	**
	x_1x_2	0.0030	1	0.0030	0.1948	0.6723	
	x_1x_3	0.1722	1	0.1722	11.09	0.0126	*
	x_2^2	0.0453	1	0.0453	2.92	0.1313	
	x_2x_3	0.2256	1	0.2256	14.53	0.0066	**
	x_3^2	0.9651	1	0.9651	62.15	0.0001	**
	Residual	0.1087	7	0.0155			
	Cor Total	5.79	16				
Shaft power P/kW	**Model**	7296.84	9	810.76	10.23	0.0029	**
	x_1	3080.73	1	3080.73	38.87	0.0004	**
	x_2	9.20	1	9.20	0.1161	0.7433	
	x_3	208.18	1	208.18	2.63	0.1491	
	x_1^2	2528.92	1	2528.92	31.91	0.0008	**
	x_1x_2	400.20	1	400.20	5.05	0.0594	
	x_1x_3	854.39	1	854.39	10.78	0.0134	*
	x_2^2	120.07	1	120.07	1.52	0.2581	
	x_2x_3	7.43	1	7.43	0.0937	0.7684	
	x_3^2	65.61	1	65.61	0.8279	0.3931	
	Residual	554.76	7	79.25			
	Cor Total	7851.59	16				

*Note: * Indicates significant impact($P<0.05$); ** Indicates a highly significant impact($P<0.01$)*

The analysis shows that the significance P values of the two evaluation index models of coefficient of variation and shaft power are all less than 0.01, indicating that the established regression model is highly significant. The coefficient of variation and the coefficient of determination of the shaft power regression model were 0.9812 and 0.9293, respectively, and the revised coefficient of determination was 0.9571 and 0.8385, respectively.

It shows that the model has a high fitting degree with the corresponding data and small test error. The model can be used to replace the test data for analysis. For coefficient of variation, regression x_1, x_2, x_3, x_1^2,

x_2x_3, x_3^2 were significant ($P < 0.01$), x_1x_3 were significant ($P < 0.05$), other effects were not significant, For axial power, regression item x_1, x_1^2 had significant effect ($P < 0.01$), x_1x_3 had significant effect ($P < 0.05$), other items had no significant effect. According to the influence significance, for the coefficient of variation, the influence degree is: stirrer height x_3 > stirrer speed x_1 > fertilizer water mixing ratio x_2; For shaft power, the influence degree is: agitator speed x_1 > agitator height x_3 > fertilizer water mixing ratio x_2.

Design-Expert 11.0 was used to draw the response surface diagram of coefficient of variation and shaft power. One of the three factors of stirrer speed, fertilizer-water mixing ratio, and stirrer height was taken as 0. The effects of the other two factors and their interaction on the coefficient of variation and shaft power were analysed, as shown in Fig. 7.

From Fig. 7a, it can be found that the variation coefficient increases with the increase of agitator speed under the same fertilizer-water mixing ratio, and increases with the increase of fertilizer-water mixing ratio under the same agitator speed. From Fig. 7b, it can be found that the variation coefficient decreases first and then increases with the increase of stirrer speed at the same stirrer height, and increases with the increase of stirrer height at the same stirrer speed. Fig. 7c shows that the variation coefficient increases with the increase of fertilizer-water mixing ratio at the same mixer height, and increases with the increase of mixer height at the same fertilizer-water mixing ratio. From Fig. 7d, it can be found that the shaft power increases with the increase of agitator speed under the same fertilizer-water mixing ratio and decreases with the increase of fertilizer-water mixing ratio under the same agitator speed. Fig. 7e shows that the shaft power increases with the increase of stirrer speed at the same stirrer height, increases with the increase of stirrer height at lower stirrer speed, and decreases with the increase of stirrer height at higher stirrer speed. It can be found from Fig. 7f that the influence of fertilizer-water mixing ratio and agitator height on shaft power is not significant, and the influence of size change on shaft power is small.

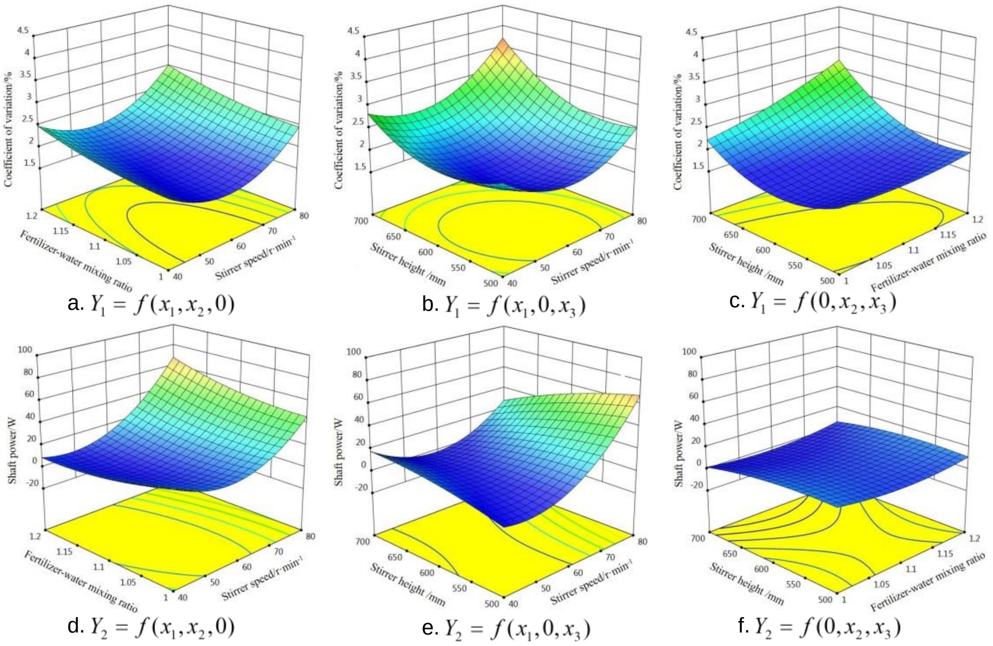


Fig. 7 - Response surfaces of interactive factors influence on test index

Numerical simulation and performance optimization of fertilizer pump

The design of the fertilizer discharge pump is based on the NL vertical sewage mud pump, which is mainly composed of a snail housing, impeller, and pump pad. The effective power formula of the fertilizer pump is as follows:

$$P_1 = \rho \cdot Q \cdot g \cdot H_2 \tag{9}$$

In equation (9): H_2 - lift, m; Q - flow, L/min; ρ - fluid density, kg/m^3; g - gravity acceleration, 9.8 m/s^2;
P_1 - effective power, kW.

In this design, the fluid in the fertilizer discharge pump belongs to solid-liquid two-phase flow. In practical work, the maximum density is about 750 kg/m^3. Therefore, we take ρ=750 kg/m^3, H_2=12 m, and Q=500 L/min here, which is obtained by Eq. (9).

Calculation formula of pump shaft power:

$$P_2 = P_1 \cdot \eta_1 \tag{10}$$

In equation (10): η_1 - pump efficiency, η_1 = 0.85. Calculated P_2 = 6.25kW.

A three-dimensional model of fertilizer discharge pump is preliminarily designed and optimized by three-dimensional drawing software. Boolean operations are used to form rotating and stationary domains to improve the accuracy of numerical simulation. After the setup is completed, the mesh is used to divide the grid. Set the unit size to 5 mm and automatically generate the grid as shown in Fig. 8. RNG k-e model is used to simulate the inside of the fertilizer discharge pump. When setting up the fertilizer discharge pump by numerical simulation, the boundary conditions are inlet, outlet, fixed wall, and moving wall. The volume fraction of solid phase must be set when setting the boundary conditions at the inlet boundary, and the external atmospheric pressure must be taken into account to set the inlet pressure; the flow around the fixed wall is the standard wall function method; and the moving wall is the impeller surface, which rotates on the Y-axis in the calculation.

To verify the performance of the drainage pump under different mixing ratios of fertilizer and water, the solid-liquid two-phase flow analysis was carried out with the mixing ratios of 0.6, 0.8, 1.0, and 1.2, corresponding to volume fractions of the second phase 0.5079, 0.5792, 06324 and 0.6737 respectively. The characteristic curves of fertilizer discharge pump with different fertilizer-water mixing ratios were obtained as shown in Fig.9.

Fig. 8 - Gridding of fertilizer pump

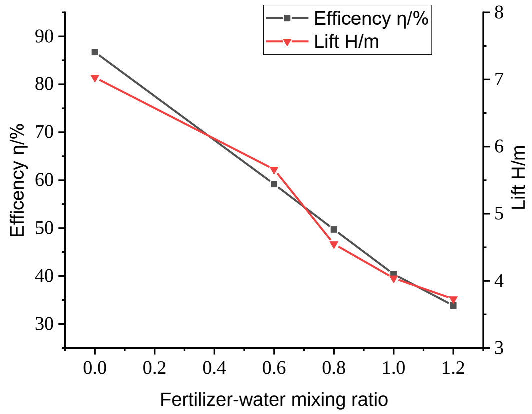


Fig. 9 - External characteristic curve

Numerical simulation of external characteristics and particle flow field of fertilizer pump

The fixed flow rate of 500 L/min is set and the speed is rated. The operating efficiency of the fertilizer pump under clean water conditions is 86.7%. With the increase of the proportion of fertilizer to the water, the working efficiency of the fertilizer pump decreases continuously. The main reason is that the higher the mixing ratio of fertilizer and water, the higher the concentration of organic fertilizer particles, the greater the obstruction to the flow path of the fertilizer discharge pump, resulting in increased hydraulic losses. The head of the fertilizer discharge pump under clean water working conditions is 7.03 m, which serves as the design head of the fertilizer discharge pump. With the increase of the proportion of fertilizer to the water, the head of the fertilizer discharge pump keeps decreasing.

At rated operating speed, 500 L/min design flow rate, and 0.3 mm average particle size of organic fertilizer, the solid-liquid two-phase flow numerical simulation of four groups of fertilizer discharge pumps with mixing ratios of 0.6, 0.8, 1.0, and 1.2 were carried out respectively. As shown in Fig. 10, with the increase of the mixing ratio of fertilizer and water, the concentration of particles in the snail housing of the fertilizer pump gradually increases; the concentration of particles at the suction outlet of the lower end of the fertilizer pump and the outer edge of the snail housing is the highest, and the concentration of particles on the working surface of the impeller is lower than that on the back of the impeller; when the mixing ratio of fertilizer and water is greater than 0.8, the distribution of particles near the outlet of the volute tongue is rather uneven; and different fertilizer pumps can suck in the fertilizer-water mixture and complete the organic fertilizer pumping out, which ensures that the organic fertilizer does not accumulate in the snail housing.

The distribution concentration of organic fertilizer particles on the outer edge of snail housing is relatively high, which is mainly due to the concentration of organic fertilizer particles on the outer edge of snail housing under centrifugal force during the process from impeller flow channel to snail housing flow channel. With the increase of mixing ratio, the concentration of organic fertilizer particles on the outer edge is more obvious. The wear of the outer edge of snail housing is easily caused by the long-term operation of the fertilizer discharge pump. Therefore, it is necessary to design the organic fertilizer particles on the outer edge design of strong snail housing.

On the whole working surface of the impeller, the particle distribution is relatively uniform, but due to the high-speed movement of the working surface of the impeller, a pressure difference is generated on the back of the impeller. The fertilizer-water mixture is pumped from the lower suction port of the fertilizer discharge pump. Under different fertilizer-water mixing ratios, the effect of the pump fertilizer is better.

Under the working conditions of 0.3 mm average particle size of organic fertilizer and 1.2 mixing ratio of fertilizer and water, four rotational speeds, 1145 r/min, 572 r/min, 381 r/min, and 286 r/min, are selected for solid-liquid two-phase flow analysis, which correspond to the rated speed, 1/2 rated speed, 1/3 rated speed and 1/4 rated speed of the fertilizer discharge pump respectively. As the speed of the fertilizer pump increases, the cross-flow speed in the impeller flow passage increases on the shaft section of the impeller, but there are obvious vortexes at the edges of both impellers far from the outlet. The vortex area is the largest at 1145 r/min and the smallest at 286 r/min. A jet high-speed area is formed near the pressure surface of the impeller at the fertilizer discharge outlet. The jet area is the largest at 1145r/min and the smallest at 286 r/min. Higher particle flow rate and jet area are conducive to increase the head of the fertilizer pump, the swirl is conducive to the mixing of fertilizer and water, but the generation of swirl will increase the hydraulic loss, resulting in a reduction of hydraulic efficiency of the fertilizer pump, and the bigger jet area, the greater the hydraulic loss will be.

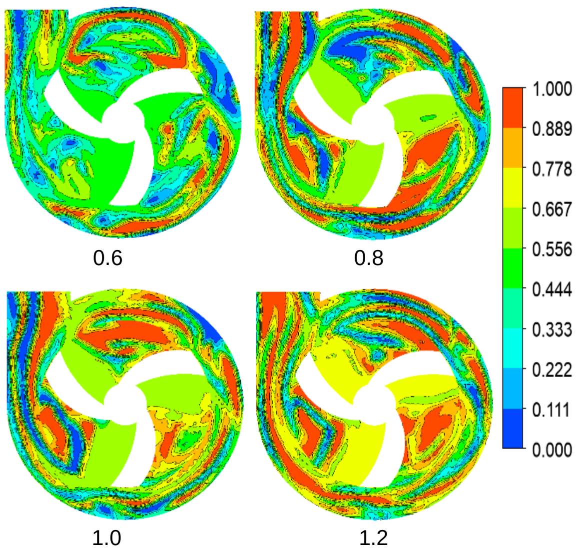


Fig. 10 - Particle distribution of organic fertilizer with different proportion of fertilizer and water

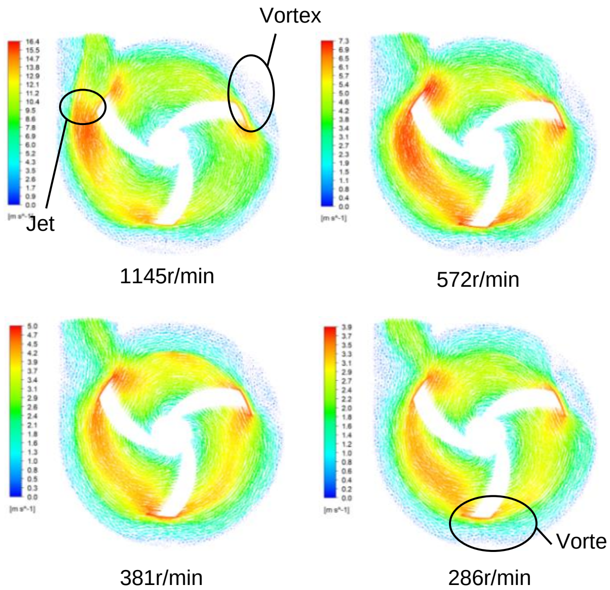


Fig. 11 - Vector diagram of relative velocity of organic fertilizer particles at different rotational speeds

Through numerical simulation, it is found that with the increase of rotational speed, the relative speed of organic fertilizer particles in the outlet increases continuously, the jet area increases, the head of the pump increases continuously, the hydraulic loss increases, and the hydraulic efficiency decreases; however, with the increase of rotational speed, the two obvious swirl areas will increase continuously, the hydraulic loss increases and the hydraulic efficiency decreases. Organic fertilizer discharge pump provides power for fertilizer injection and needs higher discharge pressure. To prevent the separation of fertilizer and water, a higher rotation speed should be selected. To increase the hydraulic efficiency of the fertilizer discharge pump, a lower rotation speed should be selected. Therefore, the speed selection of the fertilizer discharge pump needs to select a lower speed according to the specific application and on the premise of satisfying the fertilizer injection requirements.

Test Verification and Analysis

According to the actual working requirements of the agitator, it is required that the agitator mixes well and consumes less power. According to the evaluation index, we hope that the coefficient of variation is large and the shaft power is small. The priority of improving mixing effect is higher than energy consumption. The optimization solution is carried out by software and multi-objective optimization is carried out within the factor control range. It is determined that the target value of variation coefficient optimization is greater than 3.83 of the maximum value of existing tests and the target of shaft power optimization is the minimum value. The optimum solution is obtained with agitator speed x_1=80 r/min, fertilizer-water mixing ratio x_2=1.2 and agitator height x_3=700 mm.

The flow field model of the mixer was established based on the combination of the optimum parameters determined by response surface analysis. The density results of the mixtures with 10 sections after optimization were shown in Fig. 12.

The calculated average density of 10 sections is 713.16 kg/m^3, the shaft power is 24.07 kW and the coefficient of variation is 4.32 %. Compared with the results of the previous 17 groups of simulations, the optimized agitator has the smallest coefficient of variation of the average density of 10 sections and relatively small power, which proves that the optimized agitator is beneficial to improve the effect of mixing fertilizer and reduce energy consumption. The agitator shaft bears the torque of 2873.35 N•m during rotation and the force exerted on the blade surface by the mixture of organic fertilizer materials. The finite element analysis of deformation and stress distribution cloud diagram of the agitator is shown in Fig. 13.

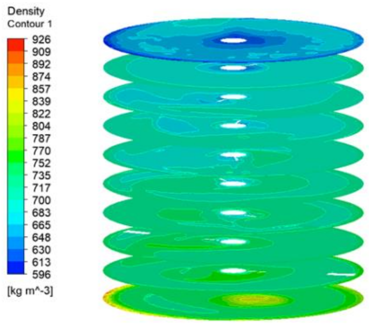
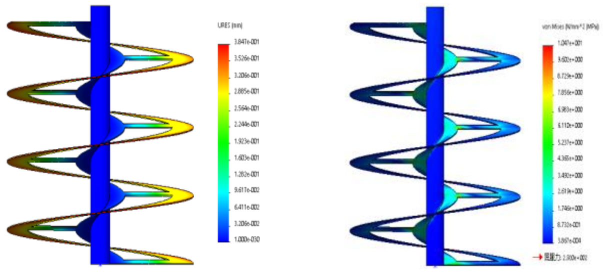


Fig. 12 - Simulation results after optimization



(a) Deformation distribution cloud map (b) Stress distribution cloud diagram

Fig. 13 - Finite element analysis of agitator

It can be seen from Fig. 13a that the maximum deformation of the agitator occurs at the edge of the screw belt with the maximum deformation of 0.3847 mm. The screw part does not deform. It can be seen that the deformation mainly occurs at the free end. From Fig. 13b, the maximum stress is 10.047 MPa at the weld between the support rod and the edge of the screw blade. At the same time, there are obvious stresses at the weld between the support rod and the screw strip and the screw blade, which are 4 MPa. The stirrer is welded with a JIS 45# steel plate. The yield strength of 45# steel is 355 MPa or more, which is much higher than the maximum stress generated by numerical simulation. The stirrer meets the working requirements.

Bench test

To verify the rationality of the optimized parameters obtained by numerical simulation, the screw-screw agitator is processed according to the optimized simulation results, and the test bench of organic fertilizer solid-liquid mixing fertilizer machine is built (screw drill is not installed), as shown in Fig. 14.

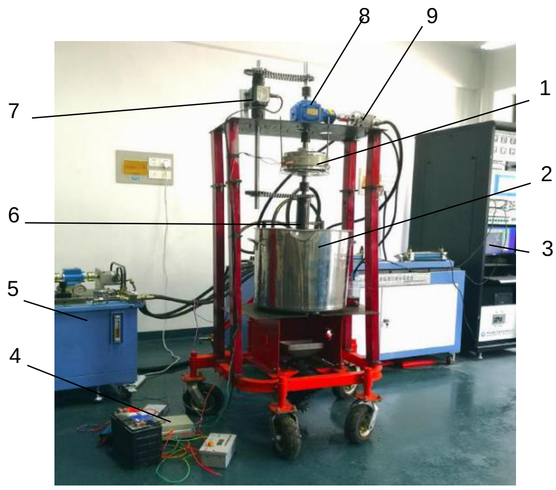


Fig. 14 - Test bench

1. Electromagnetic clutch; 2. Fertilizer drum; 3. Hydraulic comprehensive test stand; 4. Controller; 5. Hydraulic pump station; 6. Stirrer; 7. Torque speed sensor; 8. One input two output gearbox; 9. Hydraulic motor

According to the test parameters of optimization results, the performance of the solid-liquid mixing agitator and fertilizer discharge pump was tested in the laboratory of Shandong Agricultural University on June 5, 2021. The experiment was conducted in the laboratory of Shandong Agricultural University. Chicken manure composting was set by numerical simulation parameters with the height of agitator 700 mm and added into the fertilizer tank according to the fertilizer-water mixing ratio of 1.2. To prevent the separation of fertilizer and water, the rated speed of the fertilizer discharge pump is selected as the working speed. The hydraulic motor is driven to rotate by the hydraulic control system of a comprehensive hydraulic test stand for agricultural machinery. The speed of the hydraulic motor is controlled at 570 r/min. After transmission of input and output gearbox, the speed of fertilizer discharge pump is 1140 r/min and the speed of agitator is 81.4 r/min after chain wheel deceleration. The torque sensor is mounted on the intermediate shaft between the reducer and the agitator via a coupling and reads the torque directly from the controlled display of the hydraulic comprehensive test stand.

After 5 minutes of the smooth operation of the mixer, open the solenoid butterfly valve at the outlet of the fertilizer pump and engage the electromagnetic clutch 5 times in 5 seconds, T1-T5 respectively. Take 500 ml from the outlet of the fertilizer pump each time. The quality of the sample was measured with an electronic balance and the density of the mixture at the test point was also measured. Three repeated tests were carried out under the same test conditions, the results of which are shown in Fig. 15.

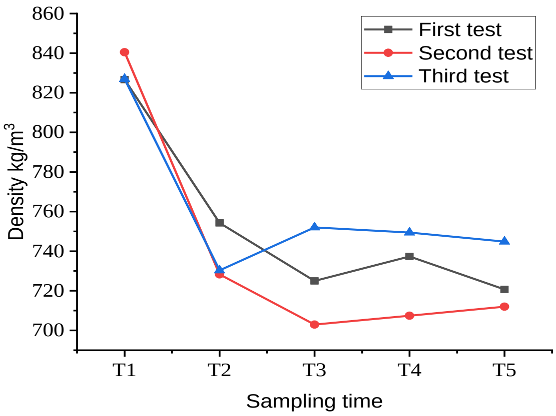


Fig. 15 - Results of three tests on the test bench

In the three tests, the density of mixture taken from T1 is higher, and the density of mixture taken from T2-T4 is consistent with the mass ratio of fertilizer-water mixture added. The possible reason is that the larger density of organic fertilizer-doped sediment is first pumped out by the fertilizer discharge pump in T1, which results in the higher density of the mixture. The results of T2-T4 show that the screw-screw mixer has a good mixing effect and the fertilizer discharge pump can completely pump the fertilizer. The test results show that when the speed of the mixer is 80 r/min, the height of the mixer is 700 mm, the mixing ratio of fertilizer and water is 1.2 and the speed of the discharge pump is 1140 r/min, the organic fertilizer mixed fertilizer is obtained with the best mixing effect, low power consumption and the effect of discharge pump can meet the working requirements of the organic fertilizer solid-liquid mixing and application device.

CONCLUSIONS

(1) A solid-liquid mixing fertilizer device for organic fertilizer in a hilly orchard was designed. According to the analysis of particle parameters and viscosity determination of various organic fertilizers, the basic structure of the screw-screw mixer was screened by numerical simulation of the mixing effect of six mixers, and the size of the fertilizer tank was designed. Through uniform mixing of fertilizer and water, an organic fertilizer applicator could directly apply organic fertilizer with different physical properties.

(2) Through two-phase flow numerical simulation and Box-Behnken design test method, 17 groups of simulation schemes were designed. The mixing effect of organic fertilizer and water during the mixing process of different mixer structures was analysed. Finally, it was determined that when the speed was 80 r/min, the height of the mixer was 700 mm and the mixing ratio of fertilizer and water was 1.2, the average density of 10 sections was 713.16 kg/m^3, the shaft power was 24.07 kW and the coefficient of variation was 4.32 %. Organic fertilizer has the best mixing effect and low power consumption.

(3) According to the optimization results of the agitator and the numerical simulation of the performance of the fertilizer discharge pump, a test bench of the organic fertilizer solid-liquid mixing fertilizer application device is set up for verification test. The test results show that the mixing effect of the test bench is good when the optimum working parameters of the agitator and the fertilizer discharge pump are 1140 r/min. The designed

agitator and the fertilizer discharge pump can meet the working requirements of field organic fertilizer application.

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