DESIGN AND EXPERIMENTAL STUDY OF HORIZONTAL-SHAFT ROLLER-TYPE COTTON STALK PULLER BASED ON RESPONSE SURFACE METHOD
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基于响应曲面法的横轴对辊式棉花拔秆机的设计与试验研究

Dangqin XUE[1] *, Zhouming GAO[2], Jiaxi ZHANG[2]
[1] Nanyang Institute of Technology, Nanyang, Henan, China;
[2] Xinjiang Agricultural University, Urumqi, Xinjiang, China.
Tel: +86037763121567; E-mail: 286409568@qq.com
Corresponding author: Dr. Dangqin Xue
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ABSTRACT

In this paper, a new horizontal-shaft roller-type cotton stalk puller was designed to address the problems of weak research on cotton stalk pulling and harvesting machines, poor agronomic adaptability, and insufficient research. First, the physical and mechanical properties of cotton stalk were experimentally studied, the cotton stalk pulling force test was conducted and the moisture content and the bending characteristics of cotton stalk were evaluated. The test results showed that cotton stalk pulling force was positively correlated with the cotton stalk diameter and the bending characteristics were positively correlated with the moisture content but were not evidently influenced by the diameter. Second, with the missed pulling rate and pull-off rate as the evaluation indexes and three independent variables, namely, forward speed, linear speed of stalk pulling rod, and rotation speed of stalk pulling roller, as the influencing factors, a 3D response surface model was established. On this basis, the lack-of-fit term P (p = 0.3650) > 0.05 of the evaluation index—missed pulling rate P1—was acquired, and the P value of pull-off rate P2 was always smaller than 0.0001. Finally, the results demonstrated that the influence of various factors on the missed pulling rate of cotton stalk is significant and followed the order forward speed > linear speed of stalk pulling rod > rotation speed of stalk pulling roller; the significance level regarding the influence on the pull-off rate followed the order rotation speed of stalk pulling roller > linear speed of stalk pulling rod > forward speed. Through the parameter optimization analysis, the optimal parameter combination was obtained which coincide with the model optimization and prediction result. The proposed method provides a basis and experimental reference for studying cotton stalk harvesting machineries.

摘要

针对棉秆起拔收获机研究薄弱，农艺适应性差，研究不足等问题，本文设计了一种新型横轴对辊式棉花拔秆机。首行进行了物理力学特性和棉秆起拔力试验，开展棉秆含水率和棉秆抗弯特性试验，结果显示棉秆起拔力与棉秆直径呈正相关关系，抗弯特性与含水率呈正相关，棉秆直径对抗弯特性影响并不明显。其次以漏拔率、拔断率作为评价响应指标，选取前进速度、拨禾杆线速度、拔秆辊转速 3 个自变量为影响因素，建立起响应面三维模型，得出评价指标棉秆漏拔率 P1 的失拟项 P（P=0.3650）>0.05，拔断率 P2 的 P 值均小于 0.0001；开展试验结果显示各因素对棉秆漏拔率的影响显著性顺序为前进速度>拨禾杆线速度>拔秆辊转速；对拔断率的影响显著性为拔秆辊转速>拨禾杆线速度>前进速度。通过参数优化得到最佳组合，与模型优化预测结果基本吻合。该装置为棉花秸秆收获机械的研究提供依据及实验参考。

INTRODUCTION

Cotton stalk is an important renewable biomass resource, which can be used as feed for poultry and are also applicable to fields such as papermaking, edible fungus cultivation, environmental protection materials, and biomass briquette fuel *(Uzair et al., 2020; Raju et al., 2019; Jinesh et al., 2022; Fawzy et al., 2021)*. If cotton stalk can be recycled, substantial economic benefits will be achieved *(Pandirwar et al., 2023)*. The current research on complete cotton stalk harvesting technology in China remains in the starting stage, without mature, efficient cotton stalk harvesting machineries in the market. Treatment methods like arbitrary discarding or incineration seriously destroy the ecological environment *(Ding et al., 2021)*.

Dangqin Xue, Prof. Ph.D. Eng.; Zhouming Gao, M.S. Stud. Eng.; Jiaxi Zhang, Prof. Ph.D. Eng

Therefore, developing stable, efficient cotton stalk harvesting machinery and equipment is the research focus of agricultural machinery.

Among the cutting-type cotton stalk harvesting machinery in China, the 4JSM-1800 cotton stalk returning to field and plastic film residue recovery combined machine designed by Wang X.N. et al. *(Wang et al., 2003)* is a representative machine type of flail cotton stalk harvester. The cutter shaft of the machine drives the movable cutter to rotate at high speed and cooperates with the fixed cutter to crush cotton stalks and scatter them into cotton fields. The disadvantage is that the stubbles less than 5 cm are flipped into the earth, hindering their rotting. In addition, the film hanging problem exists in the recovery of plastic film residue, which aggravates the operation difficulty, results in earth hanging by plow, and seriously affects the working efficiency. The representative shear-type cotton stalk harvesting machinery is the 4MG-275 self-propelled combined harvester developed by Sun Y.F. et al. *(Sun et al., 2012)*, which is not restricted by the row spacing of cotton with strong adaptability yet accompanied by stubble remaining on the ground and easy wear of the cutting knife. The operation of the machine is greatly affected by ground flatness. A representative pulling and shovel cutting-type cotton stalk harvesting machinery is the 4MB-6 row-aligned shovel pulling and laying machine for densely planted cotton designed by He X.W. et al. *(He et al., 2020)*. In the operation, this machine needs to be strictly buried in soil in a row-aligned way with a satisfactory pulling effect, but the power consumption is large, which seriously damages the mulching film. Moreover, the plastic film residue cannot be easily recovered, and the shovel cutting device is subjected to heap soil problem, failing to operate continuously for a long time and needing timely manual clearing. A toothed disc-type cotton stalk harvesting machinery *(Chen et al., 2019)* is pulling-type cotton stalk harvesting machinery, which is mainly characterized by multirow cotton stalk pulling and strict requirement for row alignment, but the missed pulling rate and the power consumption are small along with cotton stalk blocking between two toothed discs. Hence, this machine fails to operate continuously for a long time, and it is only applicable to the large single-row cotton planting mode. The 4MGB-210 self-propelled combined cotton stalk harvesting and binding machine *(Liao et al., 2021)* is toothed roller-type cotton stalk harvesting machinery, which features low energy consumption, high cotton stalk harvesting efficiency, no requirement for row alignment, and strong adaptability to row spacing, but grass may be entangled on the toothed roller, the film may be tangled, the cotton stalk cannot fall off from the toothed roller, and the conveyer device may be blocked. The 4JB-2200 suspension-type cotton stalk puller *(Shi et al., 2015) is* roller-type cotton stalk harvesting machinery, which is applicable to the planting mode with a wide row spacing but fails in large-area promotion; this machine is of high energy consumption and serious roller wear.

To sum up, cotton stalk harvesters have many kinds, all of which need row alignment. The toothed disc-type cotton stalk harvester is suitable for cotton stalk harvesting under the large single-row planting mode. Although the shovel cutting-type cotton stalk harvester works well, it needs to be buried in the soil, which has high power consumption and damages the plastic film. The roller-type cotton stalk harvester needs to work strictly under the row alignment mode, with poor adaptability to the row spacing. The mature machine type not needing row alignment smashes and returns the cotton stalk to the field or harvests cotton stalk by means of shear, but the stubbles may be left on the ground, which is not favorable for the subsequent cultivation and plastic film residue recovery. In China, diversified cotton planting modes are adopted, row spacing and plant spacing are not standard, row alignment-type operation machineries cannot be promoted in a large area, and the subsequent plastic film residue recovery is difficult in most film mulch planting modes. Thus, the physical and mechanical property test, bending resistance test, and cotton stalk pulling force test of cotton stalk were implemented. With the cotton stalk under the dense planting mode of machine-harvested cotton as the study object, a cotton stalk puller not needing row alignment and soil burying operations and not leaving stubbles was developed in this paper to solve the problems of the existing machines and tools, such as poor adaptability to row spacing, damage of mulching film, and stubble remaining on the ground.

State of the art

Chinese and foreign scholars have made some achievements in cotton stalk harvesting technology and equipment *(Mostofi , 2018; Srinidhi and Sushilendra, 2023; Fiaz et al., 2020)*. Cotton stalk harvesting machines in Australia, India, Russia, the United States, and other cotton-growing countries are relatively mature.

The KV-3.6 and KV-4 shovel cutting-type cotton stalk harvesting machines *(Ding, 2018)* produced in Uzbekistan have similar structures, and both adopt traction-type hooks; shovel-cutting devices dig into the soil to break the roots of the cotton stalks. This kind of cotton stalk harvesting method needs row alignment, the root is thoroughly shoveled, and the net yield is high, but some problems such as serious wear and tear of digging shovel and high energy consumption also exist. The Australian multi-stalk puller and the American AMADAS cotton stalk harvesting chopper use several pairs of rubber rollers installed at a certain inclination angle to rotate toward one another and then clamp cotton stalks to complete the pulling operation *(Jiang, 2016)*. Both machines adopt the rear suspension mode, and the rubber roller is driven by hydraulic pressure to rotate. The former has a wide working width and can pull out eight rows of cotton stalks simultaneously, whereas the latter can pull out three rows of cotton stalks, and the pulled cotton stalks are chopped and returned to the field by the crushing device arranged at the rear. This kind of cotton stalk harvesting method is affected by the size of the rubber roller, which has certain requirements for the row spacing of cotton in agronomy.

Dave Koenig’s cotton stalk planer and Orthman’s cotton stalk planer from the United States *(Li et al., 2008)* adopted a pair of symmetrically installed inclined disks to excavate cotton stalks. Dave Koenig’s cotton stalk planer can adjust the number of discs according to the actual needs and harvest different rows of cotton stalks. Orthman’s cotton stalk planer and digger are equipped with a chopping device, which can crush and return cotton stalks to the field after pulling out. Compared with shovel cutting, this digging-type cotton stalk harvesting has reduced energy consumption but still has strict requirements for row alignment. The cotton stalk harvesting machinery in the above countries is mature, the planting agronomic standards are normative, and the cotton stalk harvesting methods all have requirements for row alignment, which is not applicable to China. *Zhang J.X. et al. (2019)* studied the toothed disc-type cotton stalk harvester by using the Box–Behnken central composite test method and taking the missed pulling rate and pull-off rate as the evaluation indexes. At the pulling height of 66.2 mm, toothed disc diameter of 627.59 mm, and toothed disc speed ratio of 0.57, the pulling height and toothed disc speed ratio exerted significant effects on the pull-off rate and missed pulling rate of cotton stalk.

Chen et al., (2019), studied the effects of the circumferential linear speed of the toothed disc, the forward speed of the tractor, and the ratio of the circumferential linear speed of the toothed disc to the forward speed of the tractor on the cotton stalk pulling rate, the pull-off rate, and the missed pulling rate through single- and multi-factor experiments. At the constant forward speed of the tractor, the increase in the linear speed of the toothed disc helps improve the stalk pulling efficiency, and the speed ratio is the key factor affecting the stalk pulling effect. However, these two kinds of toothed disc-type cotton stalk harvesters easily cut off cotton stalks, and cotton stalks need to be pulled in a row-aligned way. *Xie J.H. et al. (2023)* determined the structural and working parameters of each part through the dynamic analysis of the cotton stalk pulling mechanism; they found that the factors of the cotton stalk pulling rate are mainly the rotation speed of the upper pulling roller, the forward speed of the machine, and the speed ratio; the factors of the missed pulling rate of cotton stalks are the speed ratio, the forward speed of the machine, and the rotation speed of the upper stalk pulling roller. However, some cotton stalks may be missed during the pulling operation.

Based on the above analysis, three-factor and three-level experiments were designed through the response surface analysis method in Design Expert software with the missed pulling rate and the pull-off rate as the evaluation indexes. Then, a 3D response surface model was constructed by taking three independent variables—forward speed, linear speed of stalk pulling rod, and rotation speed of stalk pulling roller—as the influencing factors. Next, the optimal parameter combination was found, providing a basis and experimental reference for studying cotton stalk harvesting machineries.

The remainder of this paper is organized as follows: In Section III, the mechanical and physical properties of cotton stalks are studied, the main test content includes the measurement of moisture content and bending strength of cotton stalks, and the test results render a basis for the subsequent cotton stalk puller design. In Section IV, the prototype is designed and subjected to the field experiment to investigate its operation performance. The significance of the influence of each factor on the operation performance of the machine is determined according to the experimental results. Combining the field experiment, the reasons for the experimental phenomena are analyzed, the optimal combination of working parameters for key parts is sought, the prototype is optimized, and a verification test is performed to achieve the best operation effect, providing a reference for the follow-up cotton stalk puller design. In Section V, the study results are summarized, and relevant conclusions are presented.

MATERIALS AND METHODS

Experimental study on cotton stalk pulling force

Cotton stalk pulling force is an important index parameter in the design of the cotton stalk puller. To obtain the value of the cotton stalk pulling force needed for harvesting after mechanical cotton harvesting, the measurement experiment of cotton stalk pulling force was conducted. In the entire process of completing pulling the roots of cotton stalks out of the ground, the maximum tensile force borne by cotton stalks is the cotton stalk pulling force. To reduce the test errors and acquire more real, effective test data, the cotton stalks in the test cotton field were subjected to the pulling force test through the double-diagonal five-point sampling method. Following the rules of double-diagonal five-point sampling, the test cotton field was divided into five test plots; in each test plot, 10 groups of cotton stalk pulling force tests were implemented, and the tensile force value needed to pull each cotton stalk out successfully was recorded.

The experiment was conducted by using a mobile cotton stalk pulling force measuring device *(Xue et al., 2021)* self-developed by the research group, as shown in Figure 1. The device was composed of a traveling wheel, a transmission system, a storage battery, a motor, a stalk pulling device, and a tension sensor. The device can pull cotton stalks out in a static state, and the tensile force required for pulling cotton stalks was measured by the tension sensor. In addition, the test instruments included a TJSD-750-II digital soil compactness tester, a notebook computer, a QS-WT soil moisture temperature tester, a vernier caliper, a meter ruler, and a tool set.

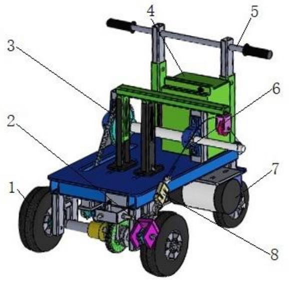


Fig. 1 - Schematic of the mobile cotton stalk pulling force measuring device
1. Traveling wheel; 2. Cotton stalk clamping device; 3. Transmission system; 4. Storage battery; 5. Handle; 6. Drag rope; 7. Motor; 8. Tension sensor

To find the relationship between cotton stalk pulling force and cotton stalk diameter, the measurement data of cotton stalk pulling force in five experimental plots were processed by Origin2018 software, and the scatter diagram of the relationship between cotton stalk diameter and cotton stalk pulling force was established, as shown in Figure 2. The cotton stalk pulling force increased with the increase of cotton stalk diameter, indicating a positive correlation between cotton stalk pulling force and cotton stalk diameter. Among 50 cotton stalks pulled out from five experimental plots, the maximum pulling force was 821N.

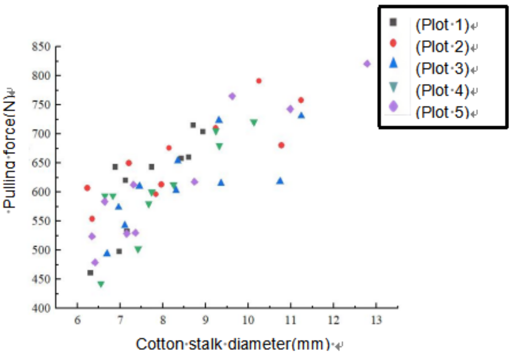


Fig. 2 - Cotton stalk pulling force–cotton stalk diameter correlation diagram

Experimental study on cotton stalk moisture content

The moisture content of cotton stalks directly affects their tensile, compressive, and bending mechanical properties *(Zhang et al., 2022)*. The experimental results can provide a theoretical basis for the follow-up experimental study on bending characteristics of cotton stalks.

The first batch of moisture content test was conducted on the day when the cotton stalk test samples were brought to the laboratory.

The moisture content was measured through the oven drying method using a PC-16A Shanghai Puchun moisture content tester, which can directly read and record the measurement results of cotton stalk moisture content. The experimental site is displayed in Figure 3-b. The second batch of cotton stalk moisture content test was performed 15 days after the first batch of test, during which natural drying was implemented. Then, the influence of the natural moisture loss state of cotton stalks on their moisture content was explored.

The cotton stalk sample variety was “XLZ No. 45”, branches were manually removed from cotton stalks with good growth momentum and without stalk damage or evident defects after harvesting with a puller. Only the main stems of the cotton stalks were reserved and manually intercepted into segments with equal length, as shown in Figure 3-a. The main instruments and equipment used in the experiment were a PC-16A Shanghai Puchun moisture content tester, a vernier caliper, a woodworking saw, scissors, stickers, a ballpoint pen, and A4 paper.

a- Cotton stalk samples *b- Cotton stalk moisture content measurement*

Fig. 3 - Field experiment photos

The two batches of cotton stalk moisture content test results are listed in Table 2. The average cotton stalk moisture contents in the first and second batches are 33.7% and 25.4%, respectively. Within 15 days of natural drying, the cotton stalks experienced certain moisture loss.

Experimental study on cotton stalk bending properties

The test result of cotton stalk bending properties is an important parameter in the design of cotton stalk pullers. The maximum bending angle bearable by cotton stalks before breakage was measured combining the bending effect on the cotton stalks during the field test of the machines and tools. The bending property parameters of the cotton stalks acquired in this manner were of direct reference values to machine and tool design, providing data support for designing cotton stalk pullers.

The bending property test results of the first batch of cotton stalks are listed in Table 1. The average moisture content of this batch of cotton stalks is 33.7%, and the maximum and minimum bending angles measured for this batch are 142.58° and 64.94°, respectively.

Table 1

Bending test results of first batch of cotton stalks

S/N	Root diameter (mm)	Bending angle (°)	S/N	Root diameter (mm)	Bending angle (°)
1	7.82	105.06	7	10.04	101.55
2	9.14	76.76	8	8.32	64.94
3	7.08	100.64	9	9.10	104.58
4	9.18	142.58	10	8.28	92.45
5	6.82	91.36	11	8.26	87.48
6	7.86	97.49	12	9.98	107.37

The bending property test results of the second batch of cotton stalks are exhibited in Table 2.

Table 2

Bending test results of second batch of cotton stalks

S/N	Root diameter (mm)	Bending angle (°)	S/N	Root diameter (mm)	Bending angle (°)
1	7.98	69.88	7	9.12	69.23
2	8.02	64.88	8	10.14	87.85
3	8.70	65.97	9	10.02	98.82
4	8.34	70.31	10	9.52	101.29
5	7.78	89.88	11	8.96	89.30
6	7.76	79.66	12	9.08	80.97

The previous section presented that the average moisture content of this batch is 25.4%, and the maximum and minimum bending angles measured for this batch are 101.29° and 64.88°, respectively.

Comparing the bending property test results of two batches of cotton stalks finds that the maximum and minimum bending angles of the second batch are smaller than those of the first batch. Only judging from the changes in the maximum and minimum bending angles of cotton stalks measures through the two tests, the bending resistance of cotton stalks weakened after moisture loss.

To explore further the relationship between the bending properties of cotton stalks and their own moisture content as well as the relationship between the bending properties and the diameter of cotton stalks, the two bending test results of cotton stalks were processed via Origin2018, and the correlation scatter diagram between the diameter and tensile strength of cotton stalks was established, as shown in Figure 4. After the second batch of cotton stalks were naturally aired for 15 days, the bending angle of cotton stalks was generally smaller than that of the first batch, once again reflecting that the bending resistance of cotton stalks would decline with the reduction of moisture content, and the bending resistance is positively correlated with the moisture content of cotton stalks. In addition, as the diameter of cotton stalks increased, the increase in the bending angle of cotton stalks displayed by the two bending property test results was not evident, manifesting that the diameter of cotton stalks is not directly related to their bending resistance.

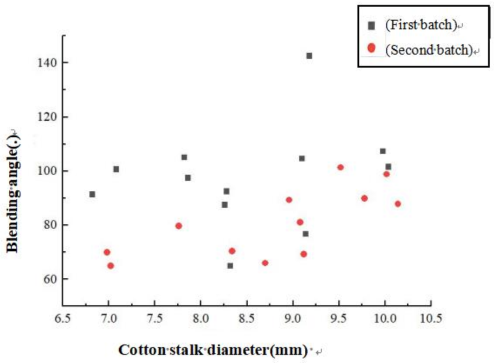


Fig. 4 - Schematic of measuring device for cotton stalk pulling force

RESULTS

Complete machine structure and working principle

The cotton stalks under the dense planting mode of machine-harvested cotton were taken as the study objects. The early-stage field survey of the cotton field revealed that the “one film for four rows” cotton planting mode is a dominant dense planting mode, the row spacing is 660 ±100 mm, and the plant spacing is about 50 mm.

Based on the above design requirements, a horizontal-shaft roller-type cotton stalk puller was developed, and the structure of the complete machine is shown in Figure 5. The device was composed of a traction frame, a stalk feeding device, a roller spacing adjusting structure, a stalk pulling device, and a transmission system. The stalk feeding device was composed of a stalk pulling rod, a toothed belt, and a pulley. The stalk pulling device mainly consisted of a pair of pulling rollers. The key working parts of the horizontal-shaft roller-type cotton stalk puller included the stalk feeding device, the pulling device, and the roller pressing mechanism.

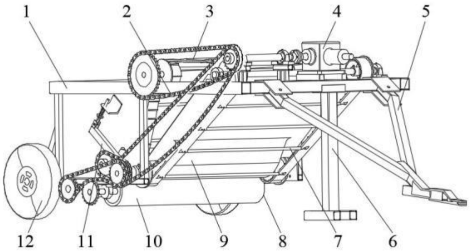


Fig. 5 - Schematic of the horizontal-shaft roller-type cotton stalk puller structure

1- Rack; 2- Transmission system; 3- Stalk feeding device; 4- Gearbox; 5- Traction frame; 6- Support frame;
7- Stalk pulling rod; 8- Stalk pulling roller; 9- Baffle; 10- Stalk pulling device;
11- Roller spacing adjusting device; 12- Traveling wheel

The horizontal-shaft roller-type cotton stalk pulling device was hung on the tractor in a traction mode of the rear suspension, and power was provided by the rear power take-off shaft of the tractor. The hanging device at the rear end of the tractor not only provided traction for the cotton stalk pulling machine but also could adjust the working heights of the stalk feeding device and the stalk pulling device.

The working process of the machine can be divided into five stages, namely, initial contact stage between cotton stalks and stalk pulling rod, stalk feeding stage, feeding stage, stalk pulling stage, and throwing stage, as shown in Figure 6.

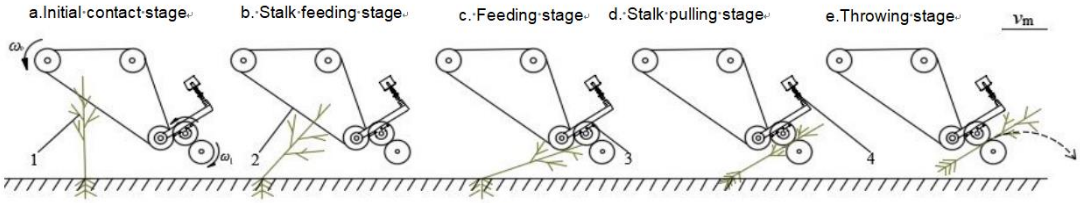


Fig. 6 - Schematic of working principles

1. Cotton stalks; 2. Stalk feeding device; 3. Stalk pulling device; 4. Roller pressing mechanism

Determination of response indexes

The test was implemented with reference to the Equipment for Harvesting-Combine Harvesters-Test Procedure (GB/T 8097-2008). In each group, the test length was 10 m, the test was implemented three times, and the average value of the three tests was taken. A test plot 300 m in length and 150 m in width was divided, and the evaluation indicators were calculated as follows:

The calculation formula for the missed pulling rate P_1 of cotton stalks is shown in equation 1:

$$P_1 = \frac{Z_1}{Z} \times 100\% \tag{1}$$

where Z_1—number of cotton stalks going through missed pulling in each group of test plot, and Z—total number of cotton stalks in each group of test plot.

The formula for the missed pulling rate P_2 of cotton stalks is shown in equation 2:

$$P_2 = \frac{Z_2}{Z} \times 100\% \tag{2}$$

where Z_2—number of pull-off cotton stalks in each group of test plot.

Determination of structural parameters and working parameters

The main factors of the working performance of the horizontal-shaft roller-type cotton stalk puller included the forward speed, the linear speed of stalk pulling rod, and the rotation speed of the stalk pulling roller, so they were taken as the influencing factors in the test. The forward speed depends on the gear adjustment of the test prototype equipped with a Changfa CFD604A wheeled tractor. According to the field test, the forward speed was about 0.56 m/s in the slow first gear, 0.78 m/s in the slow second gear, and 1 m/s in the fast first gear. The linear speed of the stalk pulling rod and the rotation speed of the stalk pulling roller were adjusted by changing the sprocket in the chain transmission system.

The Box–Behnken central composite design method was adopted in the test, and a three-factor three-level quadratic regression orthogonal test scheme was used *(Bano and Irfan, 2019)*, followed by analysis through the response surface method *(Oznur et al., 2023; Zhang and Wu, 2023)*. Moreover, a mathematical model indicating the relationship between pulling force and each factor was established to obtain the optimal combination of working parameters *(Zhu et al., 2023)*. The test factors and levels are listed in Table 3.

Table 3

Test factors and levels

Level	**Forward speed *A* (m·s^{-1})**	**Linear speed of stalk pulling rod *B* / (m·s^{-1})**	**Rotation speed of stalk pulling roller *C* / (r·min^{-1})**
-1	0.56	1.5	191
0	0.78	1.75	239
1	1	2	287

Results and significance analysis

(1) Regression analysis of missed pulling rate and pull-off rate

The test scheme and results are listed in Table 4. The test results were subjected to quadratic regression analysis by using Design Expert 8.0.6 *(Zhang et al., 2018)*, and the quadratic polynomial response surface regression models of missed pulling rate and pull-off rate for three independent variables—forward speed, linear speed of stalk pulling rod, and rotation speed of stalk pulling roller-were established, as displayed in Equations 3 and 4. Subsequently, the analysis of variance of the regression models was performed *(Esmailzadeh et al., 2021)*, and the results are shown in Table 4.

$$P_1 = 5.84 + 5.49A - 1.40B - 1.22C - 0.78AB + 0.99AC - 1.46BC + 3.92A^2 + 1.75B^2 + 1.94C^2 \tag{3}$$

$$P_2 = 132.37 - 98.86A - 63.25B - 0.29C - 14.23AB + 0.09AC - 0.12BC + 80.96A^2 + 27.94B^2 + 8.41C^2 \quad (4)$$

A - Forward speed;
B - Linear speed of stalk pulling rod;
C - Rotation speed of stalk pulling roller.

Table 4

Response surface test scheme and results

Test No.	**Factor**			**Missed pulling rate P_1 / %**	**Pull-off rate P_2 / %**
	A	*B*	*C*		
1	1	0	1	16.74	13.73
2	0	0	0	5.67	5.28
3	0	0	0	5.03	5.2
4	0	-1	1	11.62	10.28
5	0	0	0	5.49	4.91
6	1	1	0	14.64	9.13
7	0	1	1	5.83	15.63
8	-1	0	1	3.37	11.73
9	-1	-1	0	6.8	6.57
10	0	0	0	6.44	5.08
11	1	0	-1	18.04	3.6
12	0	0	0	6.56	4.31
13	0	-1	-1	10.3	2.35
14	-1	0	-1	8.63	4.6
15	1	-1	0	18.93	5.43
16	-1	1	0	5.64	7.6
17	0	1	-1	10.34	4.41

The analysis of variance in Table 5 presents that the values of P1 and P2 were smaller than 0.0001, indicating the high significance level of this regression model. The lack-of-fit term of P1 was P (P = 0.3650) > 0.05, also manifesting its high fitting degree, and its coefficient of determination was R2 = 0.9900, reflecting that the two models could explain over 98% of the evaluation indexes. Hence, the two models could optimize the working parameters of this device.

Table 5

Analysis of variance of regression equations

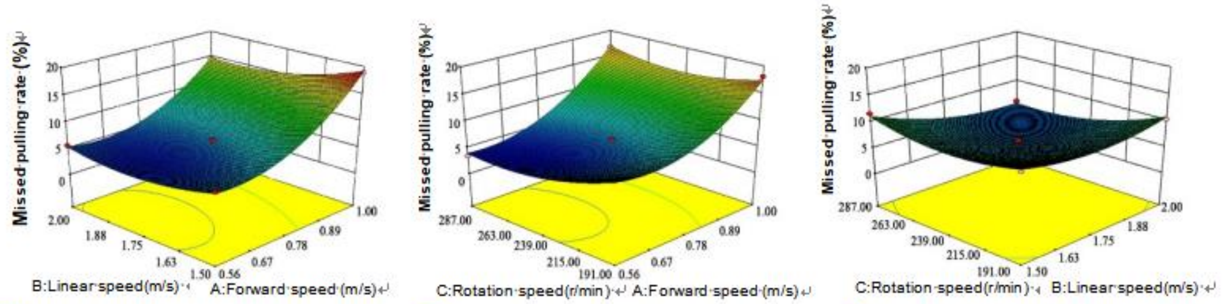
Source of variance	**Missed pulling rate / P_1**				**Pull-off rate P_2**			
	Quadratic sum	**Degree of freedom**	***F* value**	***P* value**	**Quadratic sum**	**Degree of freedom**	***F* value**	***P* value**
Model	385.69	9	86.77	<0.0001	225.56	9	88.15	<0.0001
A	241.01	1	488.01	<0.0001	0.24	1	0.85	0.3874
B	15.68	1	31.75	0.0008	18.42	1	64.80	<0.0001
C	11.88	1	24.06	0.0017	165.71	1	582.86	<0.0001
AB	2.45	1	4.96	0.0612	1.78	1	6.27	0.0408
AC	3.92	1	7.94	0.0259	2.25	1	7.91	0.0260
BC	8.50	1	17.21	0.0043	2.71	1	9.52	0.0177
A^2	64.65	1	130.91	<0.0001	6.44	1	22.66	0.0021
B^2	12.84	1	25.99	0.0014	4.12	1	14.50	0.0066
C^2	15.82	1	32.04	0.0008	20.79	1	73.12	<0.0001
Residual error	3.46	7			1.99	7		
Lack-of-fit term	1.77	3	1.40	0.3650	1.39	3	3.09	0.1519
Variance	1.69	4			0.60	4		
Sum	389.14	16			227.55	16		

(Remarks: p < 0.01 indicates extremely significant; 0.01 < p <0.05 reflects significant; p > 0.05 means insignificant)

The magnitude of P value reflected the influence degree of each parameter on the regression models. According to the P value of each factor in Table 5, all the other regression terms except AB in the P_1 model produced significant influences, among which the seven regression terms A, B, C, BC, A^2, B^2, and C^2 showed extremely significant influences; in the P_2 model, the other regression terms except A generated significant influences, among which B, C, A^2, B^2, and C^2 exhibited extremely significant influences. The F value of each factor in Table 5 shows that the significance of the influence of each factor on P_1 in descending order was A， B and C; that on P_2 in descending order was C, B and A.

(2) Response surface analysis of missed pulling rate and pull-off rate

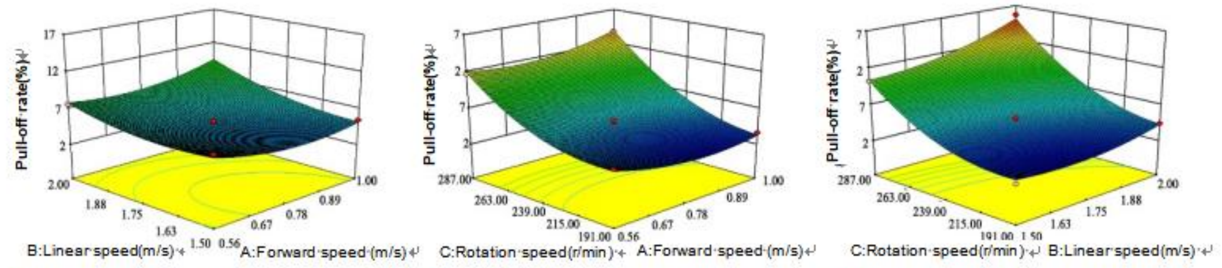
To express vividly the significance of the influence of each test factor on the working performance of the machine, a 3D response surface model *(Shi et al., 2023)* was established, and the consistency between the influencing trend of each factor on evaluation indexes and the analysis result of variance was assessed *(Jiang et al., 2024)*, as shown in Figure 7.



a. When C is 239 r/min, the influence law of A and B

b. When B is 1.75 m/s, the influence law of A and C

c. When A is 0.78 m/s, the influence law of B and C



d. When C is 239 r/min, the influence law of A and B

e. When B is 1.75 m/s, the influence law of A and C

f. When A is 0.78 m/s, the influence law of B and C

Fig. 7 - Interactive influence of test factors on missed pulling rate and pull-off rate of cotton stalks

According to the variation trend of response surface, the significance of the influence of each test factor on the missed pulling rate of cotton stalks in descending order was A > B > C, and that on the pull-off rate was C > B > A; both were consistent with the analysis results of variance. Combining the concrete field test, the reasons for missed pulling and pull-off phenomena of cotton stalks were mainly considered as follows: after machine-aided cotton harvesting, the working conditions were complicated, some cotton stalks fell over seriously, preventing the machine from completing stalk feeding; this resulted in missed pulling. At an excessively high forward speed, the machine failed to convey cotton stalks to the bottom end to complete feeding, so the stalk feeding effect was poor, leading to missed pulling; cotton stalks would be damaged to some extent by the spindle part of the cotton harvester and could be easily broken when pulled up.

Parameter optimization and test verification

To achieve the best pulling effect of the horizontal-shaft roller-type cotton stalk puller, the experimental factors that affect its operation effect need to be optimized. The table of the analysis of variance and the response surface model shows that the machine generated a good pulling effect under a slow forward speed, a medium linear speed of the stalk pulling rod, and a medium rotation speed of the stalk pulling roller. The results obtained through Design-Expert 8.0.6 show that when forward speed = 0.68 m/s, linear speed of stalk pulling rod = 1.73 m/s, and rotation speed of stalk pulling roller = 221.54 r/min, the predicted missed pulling rate of cotton stalks reached 5.06% and the predicted pull-off rate reached 3.83%, indicating that theoretically, the horizontal-shaft roller-type cotton stalk puller achieved the best pulling effect under this working state.

To verify the accuracy of the parameter combination optimized by the software, a field verification test was conducted, and the test site is shown in Figure 8. Before the test, the working parameters of the device were set to be 1.75 m/s for the linear speed of the stalk pulling rod, 221 r/min for the rotation speed of the stalk pulling roller, and 0.68 m/s for the forward speed of the unit. The test was repeated three times, and the average value of the three tests was taken as the verification value, as listed in Table 6. Under the optimal parameter combination, the missed pulling rate was 5.24%, the pull-off rate was 3.75%, and the relative error of theoretically predicted values from the average value of the three tests was always smaller than 4%, thus meeting the design requirements and proving that the parameter optimization model was reasonable.

Table 6

Optimized value and test verification value

Item	**Missed pulling rate of cotton stalks P_1 / %**	**Pull-off rate of cotton stalks P_2 / %**
Average value in the field experiment	5.24	3.75
Software optimized value	5.06	3.83
Relative error	3.44	2.13

a- Before operation *b- After operation*

Fig. 8 - Effect comparison before and after operation at the test site

CONCLUSIONS

Based on the current research status of cotton stalk pulling and harvesting machines, a new type of cotton stalk pulling machine, which could pull up the whole cotton stalk, was designed. The physical and mechanical properties of cotton stalks were studied to provide a theoretical basis for machine design. Moreover, the structural parameters and working parameters were determined, and the factors influencing the working performance of the machine were acquired. Then, the prototype was subjected to the field experiment to obtain the optimal parameter combination. Finally, the following main conclusions were drawn:

(1) According to the cotton stalk pulling force test results, the cotton stalk pulling force is positively correlated with the diameter of cotton stalks, and the maximum pulling force is 821 N. As revealed by the bending property test, the bending resistance of cotton stalks is positively correlated with their moisture content, and the diameter of cotton stalks exerts an insignificant influence on their bending resistance, with the minimum bending angle of 64.88°.

(2) The interactive influence between the response curve and influencing factors on the model, the change laws of the cotton stalk pulling force and pull-off rate under the influences of the forward speed, the linear speed of the stalk pulling rod, and the rotation speed of the stalk pulling roller were analyzed. The significance of the influence on the missed pulling rate followed the order forward speed > linear speed of stalk pulling rod > rotation speed of stalk pulling roller; the significance of the influence on the pull-off rate followed the order rotation speed of stalk pulling roller > linear speed of stalk pulling rod > forward speed.

(3) The working parameters for the horizontal-shaft roller-type cotton stalk puller were optimized by the response surface combination test method, and the regression equations for the missed pulling rate and pull-off rate of cotton stalks were optimally solved. The results show that when linear speed of stalk pulling rod = 1.75 m/s, the rotation speed of stalk pulling roller = 221 r/min, and the forward speed of the unit=0.68 m/s, the missed pulling rate and pull-off rate of cotton stalks were 5.24% and 3.75%, respectively, and the relative error of predicted values from the average value of the three tests remained smaller than 4%, thus meeting the design requirements and indicating the reasonability of the optimization model. Then, the horizontal-shaft roller-type cotton stalk puller prototype was subjected to a field experiment, and the error of the test result was smaller than 4%, indicating that the response surface method is capable of intuitive prediction and improving and optimizing equipment parameters, providing reference significance for the parameter optimization of cotton stalk pulling machines.

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