DESIGN AND EXPERIMENT ON CUTTING AND CRUSHING DEVICE OF SIDE-SWEEPING STRAW RETURNING MACHINE

/

侧扫式秸秆还田机切割粉碎装置设计与试验

Ruili WANG[1)], Deshuai LI[1)], Shuai LI[1)], Tong REN[1)], Hongbo BAI[2)], Yashuang JIN[2)], Wei WANG[1,*)], Satyanarayan R.S. DEV[3] [1]

[1)] College of Engineering, Shenyang Agricultural University, Shenyang 100866, China

[2)] Yushu City Enyu Township Comprehensive Service Center, Changchun 130408, China

[3)] College of Agriculture and Food Sciences, Florida A&M University, Tallahassee, FL 32307, USA

**Corresponding authors. Email: syww@syau.edu.cn*

DOI: https://doi.org/10.35633/inmateh-72-52

Keywords: *Straw returning to the field; Cutting and crushing device; Optimization tests*

ABSTRACT

This paper aims to solve the problems of complex structure, poor straw crushing effect and high power consumption of existing straw returning machines. A cutting and crushing device with moving and fixed blades has been developed. The moving blade has collision and automatic retraction functions, which can effectively reduce destructive damage caused by blade obstacles and extend its service life. The double-type single-support cutting method has the advantages of improving the straw crushing effect and reducing the running power consumption. The effects of blade rotational speed, blade offset angle and blade number under the condition of composite single-support cutting were tested according to the uneven ratio of straw throwing and the qualification ratio of straw crushed length. The optimal combination of working parameters of the cutting and crushing device was determined: blade rotational speed of 1968 r/min, blade offset angle of 5°, blade number of 4. The test results show that the uneven ratio of straw throwing is 17.18%, and the qualification ratio of straw crushed length is 92.23%. The operation effect of the side-sweeping straw returning machine was tested on the field. All operating indicators are equipped with cutting and crushing devices, and the results show that all operating indicators meet the technical requirements of straw return.

摘要

本文旨在解决现有秸秆深还机切割粉碎装置结构复杂、秸秆破碎效果差、功耗高等问题。设计了一种侧扫式秸秆深还机切割粉碎装置。该切割粉碎装置采用动定刀结合的设计，动刀片具有碰撞自动回缩功能，可有效降低障碍物对刀片的破坏性伤害，延长其使用寿命。采用复式单支撑的切割方式，具有提高秸秆粉碎效果和降低作业功耗等优点。本文利用自制的玉米秸秆切割粉碎试验台，以秸秆抛洒不均匀率和秸秆切碎长度合格率为目标值，对刀盘转速、偏移角度和刀片数目等影响因素进行了玉米秸秆复式单支撑切割条件下的单因素试验和中心组合试验。试验结果表明：当刀盘转速为1968r/min、偏移角度为5°，刀片数目为4 时，秸秆抛洒不均匀率为17.18%，秸秆切碎长度合格率为 92.23%。对安装了切割粉碎装置的侧扫式秸秆还田机整机作业效果进行了田间性能试验，结果表明各项作业指标均可达到国家相关标准的技术要求

INTRODUCTION

Northeast China is abundant in straw resources, corn straw is widely distributed, and the potential for use is enormous. Straw recycling is one of the most common methods of treatment and reuse at home and abroad. In some developed countries, the utilization rate of straw resources is very high, which basically solves the problem of straw piles and open burning *(Wang et al., 2017; Yeboah et al., 2017)*. By returning the straw to the field, the soil fertility can be significantly increased *(Liang et al., 2021; Dong et al., 2019; Han et al., 2020; Song et al., 2019)*. Taking straw back to the field can bring other benefits, including curing soil, wind and water erosion resistance, improved permeability, water storage, promoting drought resistance, and increased crop yield *(Liang et al., 2020; Guo et al., 2020; Li and Wang, 2020; Awad et al., 2022; Shao et al., 2023)*. Straw crushing and deep burial operation can reach 30 cm deep *(Wang et al., 2017)*.

---

[1] *Ruili Wang, Associate professor; Deshuai Li, Postgraduate; Shuai Li: Postgraduate; Tong Ren: Postgraduate; Hongbo Bai: Senior engineer; Yashuang Jin: Senior engineer; Wei Wang: Professor; Satyanarayan R S Dev: Associate professor*

It can effectively break the bottom of the plough, store water, increase the content of nitrogen, phosphorus, potassium, and other organic matter and nutrients in the soil, improve the soil tillage layer structure, promote the absorption of nutrients by crop roots, reduce the dust pollution caused by straw burning, and reduce the destructive damage caused by high temperature caused by combustion to some microorganisms in the soil *(Lin et al., 2019; Tian et al., 2018).*

At present, the corn straw crushing and returning equipment on the market is basically divided into two forms: one is the straw crushing and returning machine matching with the corn combine harvester, and the other is the straw returning machine suspended by the tractor *(Xie et al., 2022; Zheng et al., 2016)*. The analysis of the blade types of the cutting and crushing devices of different straw crushing and returning machines can be roughly divided into hammer claw type, L type or Y type and straight blade type. Hammer-claw type blade has large volume, strong hammer force and good crushing effect. However, its structure is complex, and the working power consumption and high-speed rotation are easy to cause vibration. Type L or Y blades are good for cutting and picking up, but their structure is slender and complex, and processing is more difficult. Straight blade, mostly using a moving blade and fixed blade matching cutting mode, its structure is simple, picking up and scattering effect is better, the material is lightweight, easy to replace, but its working width is small, it needs to increase the density of the blade in order to achieve a good working effect *(Jia et al., 2015; Guo et al., 2014)*. The cutting and crushing device of straw deep returning machine is the key to ensure the qualified rate of straw crushing. There is a pressing need to develop an efficient, low-consumption, simple, and reliable cutting and crushing device.

The straight blade is chosen by comparing the advantages and disadvantages of the straw returning blade in the existing straw returning machine. Based on the principle of sliding cutting, a moving fixed tool composite single support is designed. By optimizing the affecting factors of blade rotational speed, blade offset angle and blade number, the experiment index of crushing effect of the cutting and crushing device on straw is improved, and the working power consumption is reduced. The results serve as a foundation for future development of deep straw buried back in the field.

MATERIALS AND METHODS

The side-sweeping straw returning machine is mainly composed of a frame, three-point suspension device, transmission device, dust proof shell, trenching and mulching plough, depth-limiting device, anti-cutting shell, cutting and crushing device, etc. (Fig. 1). The cutting and crushing devices are mounted on the frame of the designed Side-sweeping straw returning machine and connected to the drive device. Two cutting and crushing devices are arranged from front to back, with the right on the front and the left on the back, with a keyway above the tool shaft that is connected to the pulley in the drive. Table 1 shows the main technical parameters of a straw deep returning machine with a cutting and crushing device.

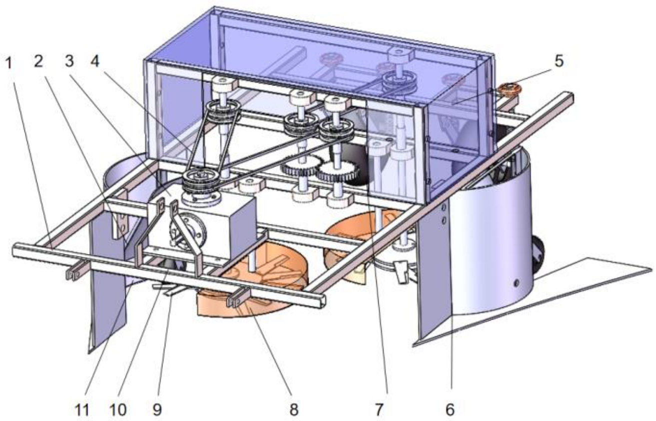

Fig. 1 - Structure of the side-sweeping straw returning machine
(1) frame; (2) three-point suspension device; (3) gearbox; (4) transmission device; (5) dust proof shell; (6) trenching and mulching plough; (7) depth-limiting device; (8) anti-cutting shell; (9) cutting and crushing device; (10) compaction wheel; (11) guide disc.

The side-sweeping straw deep returning machine is attached to the rear of the tractor through the three-point suspension device. The tractor's power output shaft uses a universal coupling to transfer the power to the transmission, which then transfers the power to the pulley and gear inside the transmission device, causing the left and right cutting and crushing devices to rotate in the opposite direction through the power transmission. The high-speed rotation of the cutting and crushing device can crush and smash the straw on the ground and throw it into the automatic plough chamber. The body of the automatic trenching and mulching plough opens the embedded ditch before the cutting and crushing device can crush the straw. The broken straw flows into the ditch through the rectangular opening of the end of the plough body. The compaction wheel installed at the opening of the plough body will press down the broken straw. Following that, trenching and mulching plough's wing broke the soil, and the soil on both sides of the plough changed the original physical structure and fell into the ditch as a result of shear, extrusion, lifting, and gravity. The broken straw is buried 30 cm underground to realize the whole straw enrichment and returned to the field.

Cutting and crushing device mainly includes cutting plate, moving blade, fixed blade, blade shaft, lock, anti-cutting shell, etc. The moving blade and the blade disc are connected by riveting, and the moving blade can rotate freely around the riveting point, and the cutting range is larger. Dynamic blade for the upper and lower double layer, fixed blade welded in the anti-cutting shell inside, located in the middle of the two layers of dynamic blade, composed of dynamic blade and fixed blade form a single cutting and crushing support.

Table 1

Main technical parameters of the straw returning machine

Items	Technical parameters
Dimension (*L*×*W*×*H*) (mm)	2500×2000×1500
Number of rows	2
Applicable row spacing (mm)	600
Working width (mm)	1200
Type of throwing blade	Straight cut H type
Trenching depth (mm)	300
Trenching width (mm)	300
Matching power (kW)	≥80
Machine mass (kg)	350

Fig. 2 shows the working principle of the cutting and crushing device. The composite single support cutting of the support blade is adopted. The blade serves as a support, the blade rotates at a high speed, and the straw is cut several times. The power of the machine is transmitted to the transmission from the tractor through the universal coupling. Through the way of power transmission, the two cutting and crushing devices are rotated in opposite directions, and the straw on the ground is crushed, thrown to the diversion plate, and transported to the ditch, to realize the deep burial of the straw.

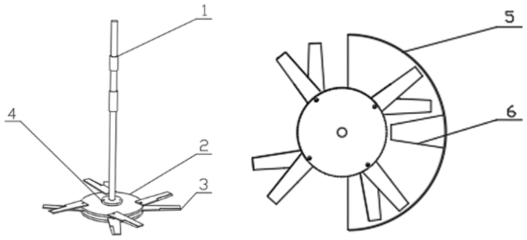

Fig. 2 - Working diagram of moving-fixed blade cutting and crushing device

(1) blade shaft; (2) blade disc; (3) moving blade; (4) lock; (5) anti-cutting shell; (6) fixed blade

Fig. 3 shows the structure of the blade, which is of the sharp H type. Four blades are installed symmetrically on each blade with a radius of 120 mm, length of 220 mm, blade opening of 140 mm and face up for repair and replacement. The upper and lower blades in each set of tools are staggered, and the angle between the upper and lower adjacent blades is 15°-25°; the distance between the disc center and the farthest end of the blade is 305 mm. On the premise that the strength of the crushing blade can be guaranteed, the blade thickness should be designed between 5-10 mm *(Zhang, 2018)*. Existing studies show that in order to ensure the straw crushing quality, the moving blade thickness should be as small as possible, so the blade thickness is designed as 5 mm *(Wang et al., 2021)*. The wider the blade, the greater the resistance of the blade crushing process, and the width of the blade will cause the weight of the straw crushing effect *(Cao et al., 2023; Liu et al., 2020)*, so the narrow end of the blade is 40 mm, and the wide end of the blade is 60 mm. The blade material is made of 65 Mn steel, and the edge of blade is treated by quenching.

The kinematic analysis refers to the qualitative or quantitative analysis of the position change of the mechanism without considering the effect of force. The kinematic analysis method was often used to study the influence of different parameter ratios of the mechanism on the change of its motion trajectory *(Ma et al., 2019)*. Based on this, the following content would use the curve drawing software SolidWorks to establish the motion trajectory model of the cutting and crushing device.

When the cutting and crushing device is working, the blade is centered around the riveting point on the blade plate and around the center of the blade disc. When rotating without load, the cutting and crushing device will experience three states, including start, stability and braking *(Liu et al., 2021; Liu et al., 2019)*. At the beginning of the start, the disc accelerates rapidly with the blade shaft. Due to inertia, the blade will have a stage lagging behind the disc, and the blade's center of mass will be deflected at a certain angle. When the disc speed is stable, the deflection angle is maximum. When the cutting and crushing device is stable, the blade has reached its equilibrium state, and the blade's center of mass is collinear with the riveting point and the center of the disc, as well as the tension of the blade on the riveting point and the centripetal force required for blade movement. When the cutting and crushing device brakes, the speed of the blade disc begins to decrease. Because of the blade's inertia, it will be ahead of the blade disc, and the blade's center will deflect at a certain angle forward. When the disc speed is stable, the deflection angle is maximum. Then the blade gradually deflects in reverse. The stable state is achieved when the blade's center of mass is collinear with the riveting point and the center of the blade disc, as shown in Fig. 4.

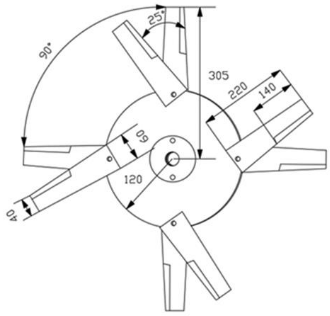

Fig. 3 - The main design parameters of blade

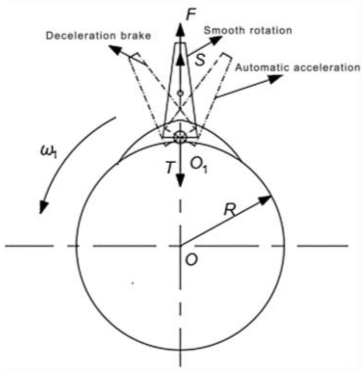

Fig. 4 - Blade motion analysis

This test was carried out on the self-made corn straw cutting and crushing tester, which consists of bench, cutting and crushing device, speed regulating motor, regulating rod, coupling, drive shaft, etc., as shown in Fig. 5. The power is output by the speed regulating motor and transmitted to the cutting and crushing device below through the drive shaft, the rear adjusting rod can adjust the deviation angle of the cutting and crushing device, the rotation speed of the cutting and crushing device can be adjusted within the range of 0 ~ 3250 rad / min, the scale range of the blade offset angle on the adjusting rod is 0°~12°, the test equipment also includes electronic scale, meter ruler, round hole sieve and vernier caliper.

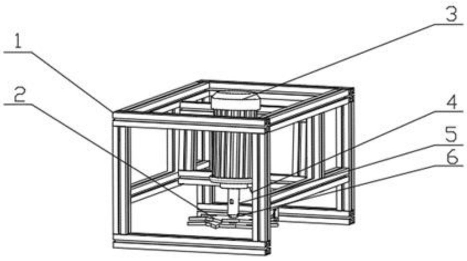

Fig. 5 - Corn straw cutting and crushing tester

(1) bench; (2) cutting and crushing device; (3) speed regulating motor; (4) regulating rod; (5) coupling; (6) drive shaft.

Blade rotational speed, blade offset angle, and blade number are the main factors of straw cutting and crushing performance, based on the principle of support sliding cutting and crushing, as well as blade dynamics analysis and kinematics analysis. Because the blade rotational speed can be controlled by the speed regulating motor, and the speed adjustment is convenient and fast, the blade rotational speed, blade offset angle and blade number are selected as the test factors. Determine the value range of each factors: blade speed 600~3000 rad/min, blade offset angle 2°~18° and blade number 2~10.

The evaluation index of straw returning machine is based on the industry standard NY/T500-2015 Operation Quality of straw returning machine. With the uneven ratio of straw throwing and the qualification ratio of straw crushed length as the test index, the influence of the blade rotational speed, blade offset angle and blade number on the test index is investigated, and the influence law of each factor on the straw cutting and crushing performance is analyzed.

During the single-factor test analysis, two factors were fixed, and the third factor was adjusted to the test. Each group of tests was repeated three times and averaged, and the effect of each factor on uneven ratio of straw throwing and the qualification ratio of straw crushed length was analyzed.

A three-factor Box-Behnken experiment was designed using Design-Expert13 software based on the previous single-factor test, as shown in Table 2, in which the center point test was repeated five times for a total of 17 trials. The relationship between the uneven ratio of straw throwing and qualification ratio of straw crushed length and the three influencing factors are shown in Table 3, where X_1, X_2, and X_3 are the coded values of blade rotational speed, blade offset angle, and the blade number.

Table 2

Factors and codes of test

Coding	Factors		
	Blade rotational speed (X_1/(r/min))	Blade offset angle (X_2/°)	Blade number (X_3)
-1	1800	4	3
0	2100	6	4
1	2400	8	5

Table 3

Experiment protocol and the results

No.	Factor level			Uneven ratio of straw throwing / %	Qualification ratio of straw crushed length / %
	Blade rotational speed / x_1	Blade offset angle / x_2	Blade number / x_3		
1	-1	-1	0	17.6	93.8
2	1	-1	0	17.5	91.2
3	-1	1	0	24.8	85.2
4	1	1	0	18.5	91.9
5	-1	0	-1	19.9	90.4
6	1	0	-1	17.9	90.6
7	-1	0	1	20.4	85.2
8	1	0	1	18.2	92.6
9	0	-1	-1	21.5	90.5
10	0	1	-1	24.7	88.9
11	0	-1	1	18.4	91.1
12	0	1	1	19.2	89.9
13	0	0	0	20.3	90.8
14	0	0	0	18.7	92.8
15	0	0	0	22.8	90.7
16	0	0	0	17.1	93.6
17	0	0	0	17.2	92.9

Straw returning to the field to cultivate fertilizer is the most direct and effective way to use straw resources. According to NY/T500-2015, the field test was carried out on the side-sweeping straw returning machine, and the qualified rate of straw crushing length, average stubble height, leakage rate and uneven ratio of straw throwing were taken as the test indexes. The tractor forward speed was 1.6 m/s, and the measurements were repeated twice.

The qualified rate of straw chopped length at each measured point is calculated according to the following formula:

$$F_h = \frac{\sum(m_z - m_b)}{\sum m_z} \times 100\% \tag{1}$$

where: F_h is qualification ratio of straw crushed length, %; m_z is the mass of straw in the measurement points, g; m_b is the mass of unqualified straw in the measuring points in terms of crushed length, g.

At each point, the stubble height of the left, middle, and right points was measured on the operating width of the straw deeper, and the average value of the three points was recorded as the stubble height of the point. The average value of the three points will be recorded as the stubble height of the point. A total of five points should be measured. The following formula calculates the uneven ratio of straw throwing:

$$\bar{m} = \frac{\sum m_z}{N_j} \tag{2}$$

$$F_b = \frac{(m_{max} - m_{min})}{\bar{m}} \times 100\% \tag{3}$$

where: m is the average mass of straw at each point within the measurement area, g; N_j is the number of measurement points in each measurement area; F_b is uniformity of spreading, %; $m_{\max}$ is maximum mass of straw at each point in the measurement area, g; $m_{\min}$ is the minimum value of straw mass at each point in the measurement area, g.

The ratio of straw missing cut is calculated according to the following formula:

$$F_1 = \frac{m_{s1}}{m_s} \times 100\% \tag{4}$$

where: F_1 is ratio of straw missing cut, %; m_s is the total amount of straw that should be returned per square meter, g; m_{s1} is the amount of straw missing cut per square meter, g.

RESULTS AND DISCUSSION

Assuming that the surface straw density of the corn harvester is certain, the cutting and crushing device of the side sweep straw deep returning machine can be considered as a swing with small deflection angle during the process from steady state rotation under no load to uniform speed movement under load. An external excitation is added to the movement of the blade around the riveting point as a result of straw obstruction, and the blade will appear repeatedly during the straw crushing process. The resistance of the surface straw to the blade f, the positive pressure N of the riveting point on the blade plate to the blade, the centrifugal force S generated by the high-speed rotation of the blade with the riveting point, and the centrifugal inertia force F generated by the high-speed rotation of the blade with the center of the blade disc are all part of the blade's main force. The force of the blade in the cutting and crushing device is shown in Fig. 6.

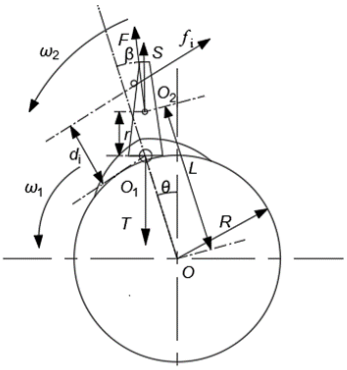

Fig. 6 - Analysis of force on blade

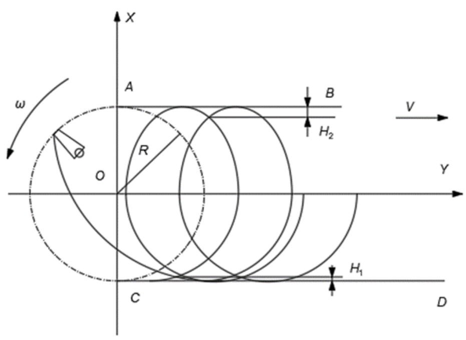

Fig. 7 - Blade motion path

Because the blade swings around the riveting point, the differential equation of the swing is:

$$J_{O1}\frac{d^2\varphi}{dt^2} = -FR\sin\theta + \sum f_i d_i \tag{5}$$

where: J_{O1} is the moment of inertia of the blade around the center O_1 of the riveting point, kg·m^2; F is inertia force, N; R - radius of the blade, mm; f_i is the resistance of the straw to the blade, N; d_i is the distance between the straw and the riveting point, mm.

$$F = m\omega_1^2 L \tag{6}$$

$$L = \sqrt{r^2 + R^2 + 2rR\cos\varphi} \tag{7}$$

where: ω_1 is the rotational speed of the blade, rad/s; m is blade mass, kg; L is distance from the center of mass of the blade to the center of the blade disc, mm; r is blade center of mass to the center of the riveting point of rotation radius, mm.

Bring formula (6) -(7) into (5), it is obtained:

$$\sum f_i d_i = J_{O1}\frac{d^2\varphi}{dt^2} + m\omega_1^2 R\sin\theta\sqrt{r^2 + R^2 + 2rR\cos\varphi} \tag{8}$$

Assuming that the density of straw is small and the resistance is small, and the blade swings around the riveting point, sinφ≈φ, cosφ≈1. Equation (7) can be written as:

$$\sum f_i d_i = J_{O1}\frac{d^2\varphi}{dt^2} + m\omega_1^2\left(R + r\right)R\sin\theta \tag{9}$$

When the side-sweeping straw deep returning machine works, the blade needs to overcome the torque of straw to cut and crush. The torque of cutting straw should be equal to the resistance torque of straw. $M=\Sigma f_i d_i$. From formula (8), the torque of cutting straw is:

$$M=J_{O1}\frac{d^2\varphi}{dt^2}+m\omega_1^2\left(R+r\right)R\sin\theta \tag{10}$$

The intersection of the blade trajectory was used to determine the spacing between the left and right blade groups, as shown in Fig. 7. The blade movement mainly consists of rotating motion and linear movement around the center of the blade, where the linear movement of the blade is provided by the tractor.

The trajectory of the blade endpoints is the cycloid. The trajectory curve equation of the blade is as follows: with the center of the blade disc as the coordinate origin, the *y*-axis direction is the forward direction of the blade disc, and the *x*-axis direction is the vertical direction, the trajectory curve equation of the blade is as follows:

$$\begin{cases} x=R\cos\omega t \\ y=R\sin\omega t+vt \end{cases} \tag{11}$$

where: t is time, s; ω is the angular velocity, rad/s; v is forward speed, m/s; R is rotation radius, mm.

The points on the edge of the envelope range of the blade movement trajectory are separated from the common tangent *AB* and *CD* of each blade trajectory, and the distances are H_1 and H_2, respectively, and the maximum values are H_1 and H_2, respectively. The maximum value is connected into a line, and the adjacent blade groups are also overlapped to obtain the appropriate blade overlap distance, reducing the re-cut area and avoiding leakage. Connect the maximum value to a line, so that adjacent tool groups also connect the line to overlap, and get the appropriate blade overlap distance, which can reduce the over-cutting area and avoid missing cutting. The overlapping distance of the leaves was 40mm after the calculation and analysis.

The results of single factor test show that (Fig. 8) when the uneven ratio of straw throwing and the qualification ratio of straw crushed length are better, the range of the blade rotational speed is 1800-2400 r/min, the range of blade offset angle is 4-8°, and the range of blade number is 3-5.

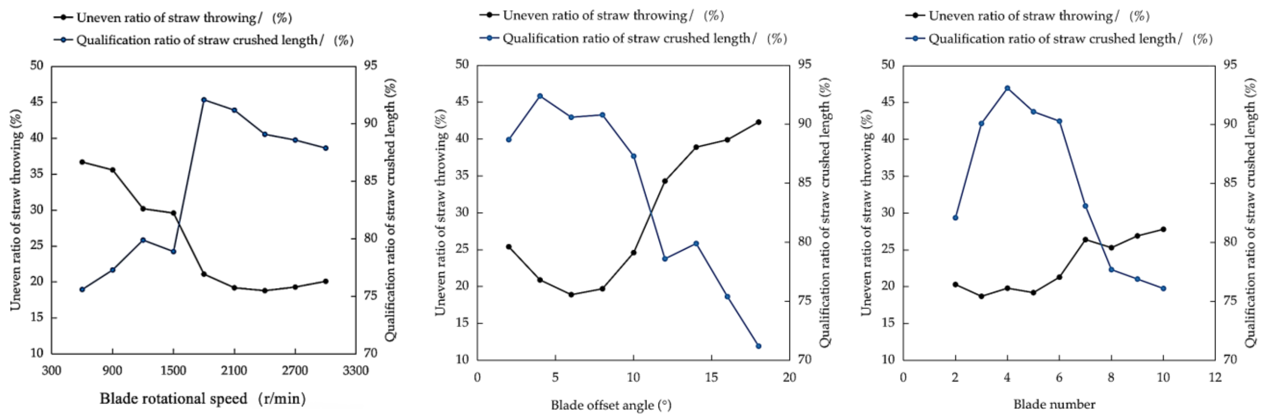

Fig. 8 - Results of single factor tests

The fitting regression analysis of the test results was performed using Design-Expert13 software to derive the regression equations for the uneven ratio of straw throwing W_1 and the qualification ratio of straw crushed length W_2, and the significance test was performed.

(1) Regression model for the uneven ratio of straw throwing W_1.

The results of ANOVA and significance test of regression coefficients for the regression model of the uneven ratio of straw throwing W_1 are shown in Table 4. The regression model's p-value (< 0.0001) for the uneven ratio of straw throwing W_1 was less than 0.01. This regression equation was highly significant. The p-value (0.9849) of the misfit term was more significant than 0. 05. The misfit term was not significant, so the fit could be used to predict the throwing unevenness rate. The regression equation for the throwing unevenness rate W_1 was:

$$\begin{aligned}\hat{W}_1 &=17.72+2.45x_1+0.61x_2+0.89x_3+0.7x_1x_3 \\ &-0.58x_2x_3+2.38x_1^2+1.25x_2^2+0.55x_3^2\end{aligned} \tag{12}$$

Table 4

Variance analysis of uneven ratio of straw throwing

Source	Sum of Squares	*df*	Mean Square	*F*-value	*P*-value
Model	95.32	9	10.59	47.51	< 0.0001**
x_1	48.02	1	48.02	215.41	< 0.0001**
x_2	3.00	1	3.00	13.46	0.0080**
x_3	6.30	1	6.30	28.27	0.0011**
x_1x_2	0.4900	1	0.4900	2.20	0.1818
x_1x_3	1.96	1	1.96	8.79	0.0210*
x_2x_3	1.32	1	1.32	5.93	0.0450*
x_1^2	23.80	1	23.80	106.76	< 0.0001**
x_2^2	6.61	1	6.61	29.63	0.0010**
x_3^2	1.29	1	1.29	5.77	0.0474*
Residual	1.56	7	0.2229		
Lack of Fit	0.0525	3	0.0175	0.0464	0.9849
Pure Error	1.51	4	0.3770		
Cor Total	96.88	16			

Note: ** indicates highly significant difference (P < 0.01), * indicates significant difference (P < 0.05), the same below.

Further analysis of each regression term of this regression equation showed that the regression terms x_1, x_2, x_3, x_1^2, and x_2^2 had a highly significant effect (P<0.01) on the throwing unevenness rate W_1, and x_1x_3, x_2x_3, and x_3^2 had a significant effect (P< 0.05) on the uneven ratio of straw throwing W_1; the effects of the other factors were not significant.

(2) Regression model of qualification ratio of straw crushed length W_2.

The results of ANOVA and significance test of regression coefficients for the regression model of qualification ratio of straw crushed length W_2 are shown in Table 5. The p-value (0.0004) of the regression model of qualification ratio of straw crushed length W_2 was less than 0.01. This regression equation was highly significant. The p-value (0.5390) of the misfit term was more significant than 0.05. The misfit term was not significant, so the fit could be used to predict the qualification ratio of straw crushed length. The regression equation of code for the qualification ratio of straw crushed length W_2 was:

$$\begin{aligned}\hat{W}_2 &= 92.96 - 1.14x_1 - 1.39x_2 - 1.3x_3 - 1.45x_1x_3 \\ &- 1.2x_2x_3 - 1.22x_1^2 - 1.17x_2^2 - 2.39x_3^2\end{aligned} \tag{13}$$

Further analysis of each regression term of this regression equation showed that the regression terms x_1, x_2, x_3, x_1x_3, and x_3^2 had a highly significant effect (P < 0.01) on the qualification ratio of straw crushed length W_2, and x_2x_3, x_1^2, and x_2^2 had a significant effect (P < 0.05) on the qualification ratio of straw crushed length W_2; the effects of the other factors were not significant.

Response surface analysis method was used to analyze the experiment data and study the relationship between the target value of straw cutting and crushing performance (uneven ratio of straw throwing and qualified rate of straw crushing length) and the influencing factors (blade rotational speed, blade offset angle, blade number) *(Wang et al., 2020; Gapparov and Karshiev, 2020)*. According to the analysis results, the response surface Fig. 9 and Fig. 10 are drawn. The response surface diagram clearly shows the influence of the influencing factors on the performance of straw cutting and crushing performance, as well as the interaction between the influencing factors on the performance.

Table 5

Variance analysis of qualification ratio of straw crushed length

Source	Sum of Squares	*df*	Mean square	*F*-value	*P*-value
Model	93.39	9	10.38	18.80	0.0004**
x_1	10.35	1	10.35	18.75	0.0034**
x_2	15.40	1	15.40	27.90	0.0011**
x_3	13.52	1	13.52	24.49	0.0017**
x_1x_2	0.3025	1	0.3025	0.5479	0.4832
x_1x_3	8.41	1	8.41	15.23	0.0059**
x_2x_3	5.76	1	5.76	10.43	0.0145*
x_1^2	6.24	1	6.24	11.31	0.0120*
x_2^2	5.74	1	5.74	10.40	0.0146*
x_3^2	24.10	1	24.10	43.66	0.0003**
Residual	3.86	7	0.5521		
Lack of Fit	1.49	3	0.4975	0.8390	0.5390
Pure Error	2.37	4	0.5930		
Cor Total	97.26	16			

Blade rotational speed, blade number, and blade offset angle were the most important influencing factors on the uneven ratio of straw throwing. There was a significant (P<0.05) interaction between the three influencing factors on the uneven ratio of straw throwing, and the main order of influencing factors on the qualification ratio of straw crushed length was blade offset angle, blade number, and blade rotational speed. There was a significant (P<0.05) interaction between the three influencing factors on the qualification ratio of straw crushed length interaction. As shown in Fig. 19 (a) and Fig.10 (a), with the increase in the blade number, the uneven ratio of straw throwing tends to decrease and then increase, and the qualification ratio of straw crushed length tends to increase and then decrease. From Fig. 9(b) and Fig.10 (b), with the increase of blade offset angle, the uneven ratio of straw throwing tends to decrease and then increase, and the qualification ratio of straw crushed length tends to increase and then decrease.

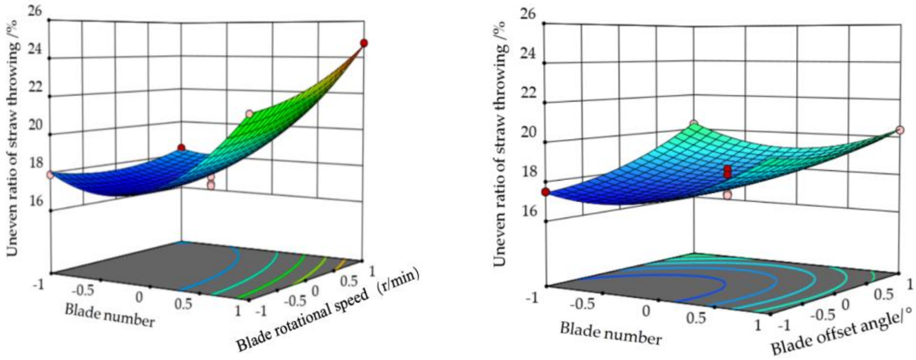

Fig. 9 - Influence of various factors on uneven ratio of straw throwing
(a) Blade rotational speed and blade number *(b) Blade offset angle and blade number*

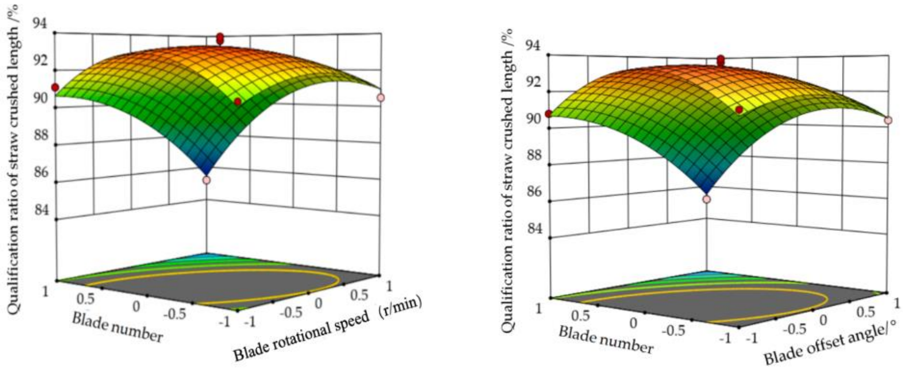

Fig. 10 - Influence of various factors on qualification ratio of straw crushed length
(a) Blade rotational speed and blade number *(b) Blade offset angle and blade number*

Using the Optimization function of Design-Expert13 software, the optimization analysis obtains the optimal parameter combination of the device: the blade speed is 1968 rad/min, the blade offset angle is 5.24° and the blade number is 4. At this time, the uneven ratio of straw throwing is 16.98%, and the qualified rate of straw crushing length is 93.59%. The working parameters of straw cutting and crushing were adjusted to the value of the preferred test factors, and the test was repeated, and the uneven ratio of straw throwing was 17.18%, and the qualification ratio of straw crushed length was 92.23%.

Field test

The field operation effect of the side-sweeping straw returning machine is shown in Fig. 11, and the field test results are shown in Table 6. The machine works well under the condition of low water content of harvested corn field and corn straw, and all the indexes can meet the design requirements.

Fig. 11 - The operation effect of side-sweeping straw returning machine

Table 6

Field test results of side-sweeping straw returning machine

Test item	Standard value	Test results
Qualification ratio of straw crushed length (%)	≥90	94.22
Average stubble height (mm)	≤80	42
Uneven ratio of straw throwing (%)	≤20	17.21
Ratio of straw missing cut (%)	≤1.5	0.81

Discussion

The results show that the optimal results obtained by theoretical calculations are very similar to the field tests, thus verifying the accuracy of simulation model building. According to the blade structure and shape in the cutting and crushing device of straw returning machine, it can be roughly divided into hanging claw type, bending blade type, Y type and straight blade type and combined bending blade type *(Gapparov and Karshiev, 2020; Lin et al., 2017)*. For example, the crushing device of 1 JKL-2 straw deeply buried back to the field is Y-type throwing blade, which rotates at high speed and cuts straw in the field operation *(Lin et al., 2022; Chinese Academy of Agricultural Mechanization Science, 2007)*. Compared with the cutting device designed in this paper, the cutting method is simple, light and easy to replace *(Zhang et al., 2021; Wang, et al., 2019)*. It can significantly improve the cutting efficiency and reduce the power consumption. The side sweeping straw cutting and crushing device designed in this paper significantly improves the blade life, reduces the damage of the obstacles to the blade, and extends the life of the blade. The compound single support cutting method has the advantages of improving the straw crushing rate and reducing the operating power consumption.

The Side-Sweeping Straw Returning Machine designed in this paper meets the design requirements, but there are still some problems worth improving, which makes the operation quality further improved. The coverage rate of the automatic coverage plough is 80.63%, which meets the design requirements, but the impact on the coverage rate can still be studied by adjusting the structural parameters, improving the coverage rate of the automatic coverage plough, using the bionic and surface spraying technology to make the cutting and crushing device more effective and reduce the resistance of the automatic covering plough in the soil, by optimizing the structure of the whole machine.

CONCLUSIONS

(1) Based on the principle of support sliding cutting and crushing, a double single support cutting and crushing device is designed, which realizes the multiple sliding cutting of the blade to the corn straw in the whole cutting and crushing process, and the straw crushing effect is good. The kinematics and dynamics analysis of the blade in the cutting and crushing device are made to ensure the simplification and lightweight of the corn straw returning machine.

(2) Three secondary response surface analysis of the test data by Design-Expert13 software, and the significance of the factors affecting the uneven ratio of straw throwing is the blade rotating speed, the blade number and the blade offset angle. The significant factors affecting the qualified ratio of straw crushing are blade offset angle, blade number and blade rotating speed.

(3) The optimal working parameter combination of the side-sweeping straw returning machine is the blade speed of 1968 rad/min, the blade offset angle of 5.24° and the blade number of 4. At this time, the uneven ratio of straw throwing is 16.98%, and the qualification ratio of straw crushed length is 93.59%. Process the side sweep straw deep returning machine according to the optimal working parameters, and the field performance test was carried out. According to the test results, the uneven ratio of straw throwing is 17.21%, and the qualification ratio of straw crushed length is 94.22%. According to the operation standard of straw returning machine to the field, and the test results meet the operation requirements. This study provides a technical basis for the industrialization of corn straw buried in the field.

ACKNOWLEDGMENTS

The authors would like to thank for Shenyang Agricultural University for providing the test instruments and equipment as well as the test site. This research was funded by the Natural Science Foundation of Liaoning Province (Grant No.2022-NLTS-19-05), and the "Jie Bang Gua Shuai" Science and Technology Program Major Project of Liaoning Province (Grant No.2022JH1/10400017).

REFERENCES

[1] Awad, R., G. M. ElMasry S. A. M. Abd El-Azeem. (2022). Influence of Incorporating Shredded Corn Stover on some Physicochemical Properties of the Soil and Corn Crop Production. *Journal of Soil and Water Sciences*, Vol.7(1), pp. 1-12. United States.

[2] Cao, S, L., Xie, J, H., Yang, Y, X., Liu, Y, R., Lu, Y, T., Sun, B. (2023). Design and experiment of side row cotton straw returning and residual film recovery combined machine (侧排式棉秸秆还田及残地膜回收联合作业机的设计与试验). *Journal of Jilin University (Engineering and Technology Edition)*, Vol. 53 (5), pp. 1514-1528. China.

[3] Chinese Academy of Agricultural Mechanization Science. (2007). Agricultural Machinery Design Manual: First Volume. *Beijing: China Agricultural Science and Technology Press*, China.

[4] Dong, L. L., Wang, H. H., Lu, C. Y., Jin, M. J., Zhu, X. L., Shen, Y., & Shen, M. X. (2019). Effects of straw returning amount and type on soil nitrogen and its composition (秸秆还田量和类型对土壤氮及氮组分构成的影响). *The Journal of Applied Ecology*, Vol. 30(4), pp.1143-1150. China.

[5] Gapparov, S., & Karshiev, F. (2020). Development chopper device that chops baled rough fodders. IOP Conference Series: *Materials Science and Engineering*, Vol. 883(1), pp.12158. England.

[6] Guo, H.Y., Zhao, S.F., Dong, Z.W., Wang, Q., Xia, D.P., Jia, J.B., Yin, X.J., Yu, H.F., (2020). Clean and efficient utilization of coal combined with corn straw by synergistic biodegradation. *Renewable Energy*, Vol.161, pp.701-711. England.

[7] Guo, Q., Zhang, X.L., Xu, Y.F., Li, P.P., Chen, C., Wu, S. (2014). Design and experiment of cutting blade for cane straw (藤茎类秸秆专用切割刀片的设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 30(24), pp. 47-53. China.

[8] Han, Y., Ma, W., Zhou, B., Yang, X., Salah, A., Li, C., Zhao, M. (2020). Effects of Straw-Return Method for the Maize–Rice Rotation System on Soil Properties and Crop Yields. *Agronomy*, Vol. 10(4), pp. 461. Switzerland.

[9] Jia, H.L., Jiang, X.M., Guo, M.Z., Liu, X.L., Wang, L.C. (2015). Design and experiment of V-L shaped smashed straw blade (V-L 型秸秆粉碎还田刀片设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 31(1), pp. 28-33. China.

[10] Li, Y., Wang, Q.B. (2020). Study on potential of straw resource nutrient return to field and application technology in China (我国秸秆资源养分还田利用潜力及技术分析). *Soil and Fertilizer Sciences in China*, Vol. (1), pp. 119-126. China.

[11] Liang, X.X., Shi, Z.L., Wang, J.C., et al. (2020). Review on the crop straw utilization technology of China. *American Journal of Environmental Science and Engineering*, Vol. 4(4), pp. 61-64. American.

[12] Liang, Y., Al-Kaisi, M., Yuan, J., Liu, J., Zhang, H., Wang, L., Ren, J. (2021). Effect of chemical fertilizer and straw-derived organic amendments on continuous maize yield, soil carbon sequestration and soil quality in a Chinese Mollisol. *Agriculture, Ecosystems & Environment*, Vol. 314, pp. 107403. Netherlands.

[13] Lin, H., He, J., Li, H., Wang, Q., Lu, C., Yang, W., Chang, Y. (2022). Design and Experiment of a Reciprocating Intermittent Chopping Device for Maize Straw Returning. *Agriculture*, Vol. 12(2), pp. 220. Switzerland.

[14] Lin, J., Ma, T., Li, B.F. (2017). Design and test of 1JHL-2 type straw deep burying and retuning machine (1JHL-2 型秸秆深埋还田机设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 33(20), pp. 32-40. China.

[15] Lin, J., Zhang, T.J., Chen, B., Han, W., Lv, Q.L., Wang, J.Q. (2019). Design and Test of Subsoiling Rotary Rilling and Rilling Combined Operating Machine (深松灭茬旋耕起垄联合作业机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 50(2), pp. 28-39. China.

[16] Liu, J. B., Bao, Y., Zheng, W. T., & Hayat, S. (2021). Network coherence analysis on a family of nested weighted n-polygon networks. *Fractals*, Vol. 29(08), pp. 2150260. United States.

[17] Liu, J. B., Zhao, J., Min, J., & Cao, J. (2019). The Hosoya index of graphs formed by a fractal graph. *Fractals*, Vol. 27(08), pp.1950135. United States

[18] Liu, P., He, J., Li, Y.J., Li, H.W., Wang, Q.J., Lu, C.Y., Zhang, Z.G., Li, S.H. (2020). Design and experiment of double rollers maize stalk chopping device with different rotation speeds (异速对辊式玉米秸秆粉碎还田装置设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 36(14), pp. 69-79. China.

[19] Ma, P.Y., Li, S.J., Zhao, C.Q., Zhang, Y.L., Zhang, X.C., Zhang, C.Y. (2019). Design and test of the orange garden profile mower cutter (柑橘园仿形割草机切割器的设计与试验). *Journal of Huazhong Agricultural University*, Vol. 38(06), pp. 156-162. China.

[20] Shao, J., Gao, C., Afi Seglah, P., Xie, J., Zhao, L., Bi, Y., & Wang, Y. (2023). Analysis of the Available Straw Nutrient Resources and Substitution of Chemical Fertilizers with Straw Returned Directly to the Field in China. *Agriculture*, Vol. 13(6), pp.1187. Switzerland.

[21] Song, X., Sun, R., Chen, W., & Wang, M. (2019). Effects of surface straw mulching and buried straw layer on soil water content and salinity dynamics in saline soils. *Canadian Journal of Soil Science*, Vol. 100(1), pp, 58-68. Canada.

[22] Tian, Y., Lin, J., Li, B.F. (2018). Design and test of conveying device of pneumatic straw deep burying and returning machine (气力式秸秆深埋还田机输送装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 49(12), pp. 36-44. China.

[23] Wang, J., Wang, X.Y., Li, H.W., He, J., Lu, C.Y., Liu, D. (2021). Design and Experiment of Rice Straw Chopping Device for Agitation Sliding Cutting and Tearing (水稻秸秆激荡滑切与撕裂两级切割粉碎装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 52(10), pp. 28-40. China.

[24] Wang, J.W., Tang, H., Wang, J.F. (2017). Comprehensive Utilization Status and Development Analysis of Crop Straw Resource in Northeast China (东北地区作物秸秆资源综合利用现状与发展分析). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 48(5), pp. 1-21. China.

[25] Wang, R., Yang, P., Rabiu, F., & Dou, S. (2017). Design and experiment of combine machine for deep furrowing, stubble chopping, returning and burying of chopped straw (秸秆深埋还田开沟灭茬机设计与试验). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 33(5), pp. 40-47. China.

[26] Wang, S.W., Li, S.J., Zhang, Y.L., Wan, Q., Chen, H., Meng, L. (2019). Mole toe bionics and surface heat treatment improving resistance reduction and abrasion resistance performance of toothed ditching blade (鼹鼠趾仿生及表面热处理提高齿形开沟刀减阻耐磨性能). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 35(12), pp. 10-20.

[27] Wang, X.Y., Zhu, S., Li, X.Q., Li, T.X., Wang, L.L., Hu, Z.X. (2020). Design and Experiment of Directional Arrangement Vertical and Horizontal Cutting of Seed Potato Cutter (定向排列纵横切分马铃薯种薯切块机设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 51(6), pp. 334-345. China.

[28] Xie, R.-Z., Ming, B., Gao, S., Wang, K.-R., Hou, P., Li, S.-K. (2022). Current state and suggestions for mechanical harvesting of corn in China. *Journal of Integrative Agriculture*, Vol.21(3), pp. 892-897. China.

[29] Yeboah, S., Lamptey, S., Zhang, R., & Li, L. (2017). Conservation Tillage Practices Optimizes Root Distribution and Straw Yield of Spring Wheat and Field Pea in Dry Areas. *Journal of Agricultural Science*, Vol. 9(6), pp. 37-48. United States.

[30] Zhang, Y., Qiao, C.X., Wang, T.Q., Cao, J.F., Wang, P.F., Shi, L. (2021). Drag reduction mechanism of the 3D geometry of foreleg's claw toe of the mole cricket (*Gryllotalpa orientalis*) (蝼蛄前足爪趾三维几何构形的减阻机理). *Transactions of the Chinese Society of Agricultural Engineering*, Vol. 37(19), pp. 309-315.

[31] Zhang, Z.Q. (2018). *Research on corn straw chopping and spreading machine design and dynamic characteristic of straw (玉米秸秆粉碎抛撒还田机的设计与秸秆运动特性研究)*. Beijing: China Agricultural University. China.

[32] Zheng, Z.Q., He, J., Li, H.W., Xi, P.S., Wang, Q.J., Zhang, X.C. (2016). Design and experiment of straw-chopping device with chopping and fixed knife supported slide cutting (动定刀支撑滑切式秸秆粉碎装置设计与试验). *Transactions of the Chinese Society for Agricultural Machinery*, Vol. 47(S1), pp. 108-116. China.