

Article

Coupled Bionic Design Based on Primnoa Mouthpart to Improve the Performance of a Straw Returning Machine

Jiale Zhao ¹, Xiaogeng Wang ², Jian Zhuang ¹, Huili Liu ¹, Yijia Wang ^{3,*}  and Yajun Yu ^{2,*}

- ¹ Key Laboratory of Bionics Engineering, Ministry of Education, Jilin University, Changchun 130025, China; zhaojl@jlu.edu.cn (J.Z.); Zhuangjian@jlu.edu.cn (J.Z.); congyj1970@outlook.com (H.L.)
- ² College of Biological and Agricultural Engineering, Jilin University, Changchun 130025, China; wxg20@mails.jlu.edu.cn
- ³ Department of Industrial and Manufacturing Systems Engineering, The University of Hong Kong, Hong Kong, China
- * Correspondence: yijia.wang@connect.hku.hk (Y.W.); yuyajun@jlu.edu.cn (Y.Y.); Tel.: +86-166-297-4902 (Y.W.); +86-151-4317-3701 (Y.Y.)

Abstract: The high energy consumption and low crushing length qualification rate of traditional straw returning machines in the main maize-growing regions of northeast China make it difficult to promote straw returning operations in the region. The primnoa locust mouthpart is extremely efficient in cutting maize rootstocks. In this paper, it was found that there are significant differences between the primnoa locust mouthpart and the conventional machine, these exist mainly in the cutting edge structure and cutting motion. Thus, this paper develops a coupled bionic design for structural and kinematic coupling elements to develop a bionic straw returning machine. This paper found that the operating performance of the bionic straw returning machine was mainly affected by the blade rotation radius and the output rotation speed of the drive mechanism through DEM (discrete element method) simulation, and the optimal combination of the two parameters was 248 mm rotation radius and 930 r/min output rotation speed. Finally, this paper finds that the most obvious operational performance difference of the bionic straw returning machine compared with the traditional straw returning machine is that it can reduce the cutting power consumption by 9.4–11.7% and improve the crushing length qualification rate by 10.4–14.7% through the operational performance comparison test. Based on the above findings, this paper suggests that in future research and development of straw returning machines, more attention can be focused on finding suitable bionic prototypes and improving bionic design methods.



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Keywords: straw returning; coupling bionic; cutting energy consumption; crushing length qualification rate; maize straw

1. Introduction

The soil type in the maize-growing region of northeastern China is a very rare cold black soil [1,2], which forms at a rate of 1 cm/400 years [3,4] and is a precious resource common to all mankind [5]. However, the rate of black soil erosion has reached 1 cm/year due to the difficulty of promoting straw returning operations in the region [6,7]. Straw returning means that crop straw is crushed into pieces no larger than 10 cm and then retained in the farmland [8], which is currently recognized as one of the most effective means to inhibit soil erosion [9]. Therefore, if the straw returning operations can be promoted on a large scale in the region, it can effectively protect the black soil resources in the region.

The main reason why straw returning cannot be rapidly promoted in the maize-growing region of northeast China is that traditional straw returning machines are difficult to apply to this region [10–12]. The planting cycle is long (6 months) in the maize growing region of northeast China [13]. Maize rootstocks are extremely thick and high in water

content after maturity [14,15], resulting in extremely high power consumption [10,11] and low qualification rate of crushing length during the operation of traditional straw returning machines [12]. Related studies have shown that, compared to other maize-growing regions in China, traditional machines will improve the operational power consumption by 6–10% when operating in the maize-growing regions of northeast China [10,11,16], and the crushing length qualification rate will be reduced by 3–5% [12,17]. Higher operational power consumption can significantly increase the cost of maize production [17]. Lower crushing length qualification rate will enhance the difficulty of sowing operations in the second year, which in turn will result in lower maize yield [18]. The above-mentioned problems have seriously affected the motivation of agricultural producers to promote straw returning operations [19]. Obviously, if a brand-new machine with efficient cutting capacity can be developed, it can significantly enhance the progress of straw returning in the region.

The unique functions of organisms have been a source of creativity for humans to achieve technological breakthroughs [20]. Researchers studying an insect unique to northeastern China (primnoa, which feeds mainly on maize stalks) found that its mouthparts were far more efficient at cutting maize stalks than traditional straw returning blades [21]. The power consumption of the primnoa mouthparts gnawing on the corn rootstocks was only 23% of that of the traditional return blade [22]. The crushing length qualification rate of the traditional straw returning blades can only be maintained at 80% [23], which is due to its cut-off success rate of only about 70% for a single cut [24], while the cut-off success rate of the primnoa mouthpart is nearly 100% for each gnawing action [25]. Coupled bionics is an emerging design approach [20], which can replicate the unique functions of organisms onto mechanical equipment [20]. Therefore, it is highly likely that the operational performance of straw returning machines can be substantially improved by coupled bionic design if the bionic coupling element with efficient cutting ability of the primnoa mouthparts can be clarified.

In summary, this paper develops a completely new bionic straw returning machine by specifying the bionic coupling elements that can improve the efficiency of cutting operation, and integrating the coupled bionic design and DEM simulation parameter optimization test. The effect of different bionic coupling elements on the operational performance and the actual operational performance of the bionic straw returning machine were verified by soil bin tests. The research in this paper can provide a new research idea and method for the design of straw returning machines. At the same time, it can promote the promotion of conservation tillage in northeastern China and slow down the rate of soil erosion of black soil resources in the region, which is of great ecological significance.

2. Materials and Methods

2.1. Bionic Coupling Element Selection and Coupled Bionic Design

The search for the bionic coupling element of the primnoa mouthpart with efficient cutting ability should start from the main differences between it and the traditional straw returning machine. As shown in Figure 1a, the main difference between the primnoa mouthpart and the traditional straw returning machine is the cutting edge geometry and the cutting motion. The cutting edge structure of the primnoa mouthpart is a segmented-serrated structure, while the cutting edge of the traditional straw returning blade is smooth curve. The primnoa uses a motion with two mouthparts rotating in equal and opposite directions to gnaw on the corn rootstalk. Traditional straw returning machines commonly use a motion in which all blades rotate in the same direction to cut maize rootstocks. In this paper, based on the uniqueness of the structure and motion coupling elements of the primnoa mouthpart, the bionic straw returning blade based on the bionic structure coupling elements and the isokinetic reverse bionic drive mechanism based on the bionic motion coupling elements are designed respectively.

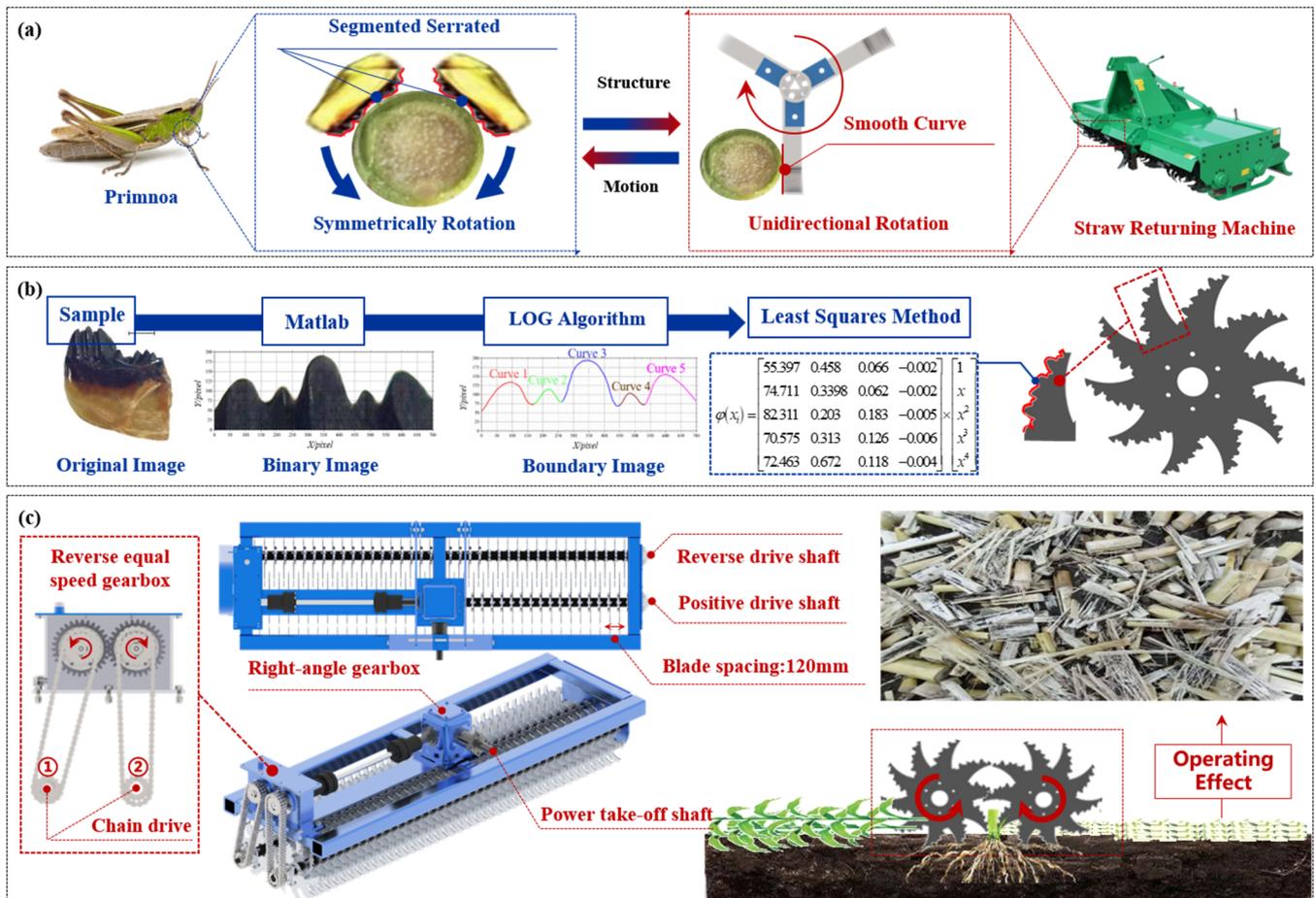


Figure 1. The search for the bionic coupling element of the primnoa mouthpart with efficient cutting ability should start from the main differences between it and the traditional straw returning machine. (a) Analysis of the difference between the primnoa mouthpart and the traditional straw returning machine. (b) Design process of bionic straw returning blade based on structural coupling elements. (c) Operating principle of bionic isokinetic reverse drive system based on motion coupling elements.

As shown in Figure 1b, the bionic straw returning blade achieves a high degree of reduction of the primnoa mouthpart. In the first step, 30 primnoa mouthparts samples were collected, and thus the original images were obtained. In the second step, the 30 original images were imported into MATLAB software (The Mathworks, Natick, MA, USA), and the multi-image fitting process was performed on the contour map of locust mouthparts using the function commands of `rgb2gray`, `imeroode`, `imdilate`, `im2bw`, `Imfill` and `edge`, respectively, and then the fitted binary images were obtained. In the third step, the binary image is plotted as a boundary image by LOG algorithm. In the fourth step, the binary image is divided into five bionic curves according to the image curve continuity characteristics, and the bionic curve parameter equation $\varphi(x_i)$ is obtained on Origin software using LS algorithm. Finally, the laser cutting operation is carried out by CNC (Shandong Ruiji CNC Machine Tool Co., Ltd., Tengzhou, China) machine according to the affine curve $\varphi(x_i)$ to obtain the affine straw returning blade.

As shown in Figure 1c, the isokinetic reverse bionic drive mechanism consists of a power input shaft, a right-angle gearbox, an isokinetic reverse gearbox, a forward drive shaft, and a reverse drive shaft. During operation, the power input shaft delivers the torque to the equal-speed reverse gearbox through the right-angle reduction gearbox. The equal speed reverse gearbox converts the torque into forward and reverse torque at the same time, and transmits the forward and reverse torque to the forward and reverse blade shafts respectively through chain drive ① and chain drive ②. The bionic straw returning blades

on the forward and reverse drive shafts are arranged in a staggered manner with a spacing of 120 mm between adjacent blades on the same blade shaft. The above design allows the bionic straw returning machine to highly recreate the way the locust mouthparts cutting the maize rootstalk.

2.2. Parameter Optimization Experiment of Bionic Straw Returning Machine Based on EDEM2018

The core operational performance of the straw returning machine is the cutting power consumption and crushing length qualification rate [21], so both were selected as test indicators. Numerous studies have shown that the two test indicators mainly depend on the rotational radius of the blade and the output rotation speed of the drive mechanism [26], so they are mainly optimized for both.

A total of three 3D simulation models of the bionic straw returning machine, soil and maize straw were required for the DEM (discrete element method) simulation experiments. As shown in Figure 2a, a single-sphere model was chosen as the soil particle model, and the Hertz-Mindlin with bonding contact model was used between each soil particle. A vertical load was applied on the surface of all soil particles to provide a compaction effect. Each physical parameter of the soil model after the above treatment is highly similar to the actual situation in the region [27]. As shown in Figure 2b, the single-sphere particle model was selected as the straw model, and the Hertz-Mindlin with bonding contact model was used between the single-sphere particle models, and each physical parameter setting of the straw model was highly similar to the actual situation in the region [14]. As shown in Figure 2c, CATIA V5R21 software (Dassault Systèmes, Paris, France) was used to build the 3D solid model of the bionic straw returning machine, and its material properties were all the same as the solid prototype. As shown in Figure 2d, the operation process was simulated by the Creator and Simulator modules in officially licensed genuine EDEM2018 software (Altair Engineering, Inc., Troy, MI, USA), and the power consumption and crushing length qualification rate of the operation were calculated by the Total Energy and Torque modules. The amount of straw returning is generally 30%, 50%, 80% and 100% in the maize growing regions of Northeast China [8,28]. In order that the results obtained from the parameter optimization experiments could maximize all the returning amounts, the straw returning amount was taken as the middle value of 65% in the DEM simulation experiments.

Since the DEM simulation test significantly reduces the test cost, a 2-factor, 5-level full-scale test is used in this paper. Five levels of rotation radius R were selected: 200, 225, 250, 275 and 300 mm. The output rotation speed was selected at 600, 900, 1200, 1500 and 1800 r/min. All the experiments were conducted in a total of 25 groups, and each group was repeated 5 times. Finally, according to the test results, the influence law of the 2 test factors on the test index was analyzed, and a regression analysis model was established, and then the optimal design parameter value combination was optimized.

2.3. Bionic Straw Returning Machine Operational Performance Test

The purpose of this test was to verify the effects of different bionic coupling elements on the operating performance and the operating effect of the bionic straw returner under different return volume conditions. Therefore, the experiment selected the bionic coupling element and straw return volume as the test factors, and the operating power consumption and crushing length qualification rate as the test indexes.

The bionic coupling element was set up in four levels: bionic structure coupling element + bionic motion coupling element (BB + BD), bionic structure coupling element + traditional drive method (BB + TD), bionic motion coupling element + traditional blade structure (TB + BD), and traditional blade structure + traditional drive method (TB + TD). The machine used for this experiment was a bionic straw returning machine with 1JGH-2 straw returning machine (the most common model in the region [29]). Before the start of each experiment, the selection of the test machine was made according to the set level of the bionic coupling element, based on Table 1.

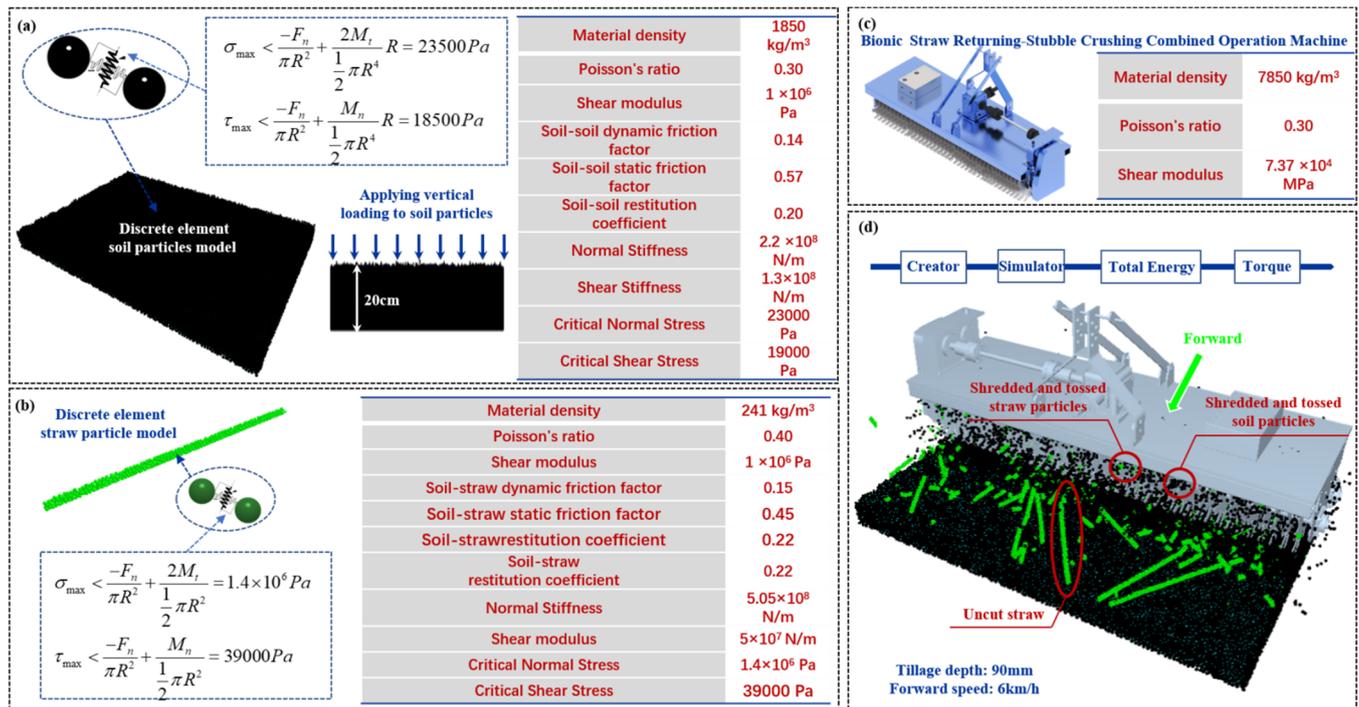


Figure 2. DEM simulation model construction and simulation operation process. (a) Discrete element soil model and parameter construction. (b) Discrete element maize straw model and parameter construction. (c) Construction of 3D model and parameters of the bionic straw returning machine. (d) The DEM-based simulation of the operation process of the bionic straw returning machine.

Table 1. Bionic coupling element level and the test machines comparison table.

Bionic Coupling Element Levels	Test Machine Selection
BB + BD	Soil bin test using a bionic straw returning machine
BB + TD	Installing the Bionic straw returning-Stubble cleaning universal blade on the 1JGH-2 Straw returning machine for soil bin test
TB + BD	Installing the traditional straw returning-Stubble cleaning universal blade on the bionic straw returning machine for soil bin test
TB + TD	Soil bin test with 1JGH-2 straw returning machine

The maize planting density in the northeast China maize growing region is 75,000 plants/hm² [30]. The effective test area of the soil bin (Agricultural Machinery Soil Bin Laboratory, Jilin University, Changchun, China) used in this paper was 80 m². Therefore, four levels of straw returning were set for the soil bin tests, 180, 300, 480 and 600 straws, according to the common return levels (30%, 50%, 80% and 100%) in the area. Before the start of each test, straw and root stubble were evenly spread or buried in the bins according to the set straw returning level.

The environmental conditions of the soil bin were made similar to the field environment by manual soil preparation, watering and compaction before the test, and the moisture content and compactness of the soil trough before the test are shown in Table 2. Post-harvest maize rootstocks were collected and sealed before the test. During the test, the maize rootstocks were removed from the plastic sealing bag to minimize water dissipation.

Table 2. Indicators of the soil in the soil bin before the test.

Soil Parameters	Soil Bin for Test	Average Maize-Growing Region in Northeast China
soil type	black clay	black clay
Soil compactness (MPa)	0.99 ± 0.04	1.03 ± 0.06
Soil moisture content (% d. b.)	19.6 ± 0.9	20.1 ± 1.2

Note: The data in the Table is from Inner Mongolia Statistical Yearbook 2020, Heilongjiang Province Statistical Yearbook 2020 and Jilin Province Statistical Yearbook 2020. The data in the table are the average of the corresponding test sites for nearly 20 years [31–33].

As shown in Figure 3a, the machine is connected to the bench test vehicle, and the test relies on the input power of the bench test vehicle (produced by Harbin Aoshen Technology Co., Harbin, China, Power output range: 0–25 kW, rotation speed output range: 2000 r/min), and the forward speed is selected as the most common 6 km/h [34]. The TQ-660 torque sensor (produced by Beijing Shitong Technology Co., Beijing, China, range: 0 ± 500 Nm, accuracy: 0.5 V) is connected to the drive shaft of the blade through a coupling, and then the torque of the machine operation is measured in real time. As shown in Figure 3b, the torque sensor can transmit the cutting resistance torque to the computer in real time, and the test data in the effective test area is fitted to the time-torque curve $g(t)$ by MATLAB software, and the operating power consumption is derived according to Equation (1). As shown in Figure 3c, the straw crushing length was measured manually, and the crushing length qualification rate was derived according to Equation (2).

$$Q = \int_0^{L/V} g(t) dt \quad (1)$$

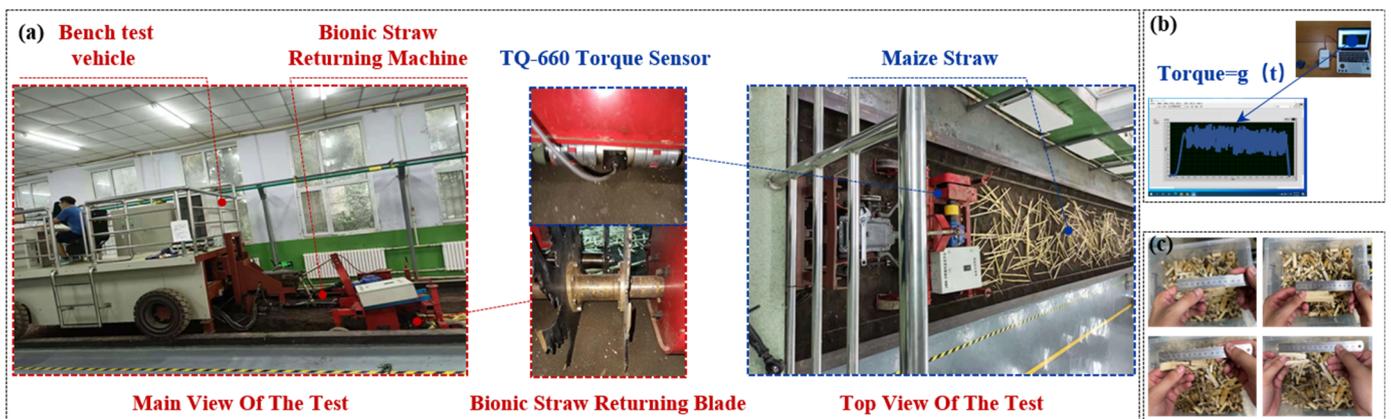


Figure 3. Soil bin test procedure. (a) Test equipment linking method. (b) Cutting energy consumption test data output. (c) Manual test results of crushing length qualification rate.

Note: Q means cutting energy consumption, L means Effective length of soil bin, V means forward speed of bench test vehicle, $g(t)$ means instantaneous torque-time function equation, t means operation time.

$$Y = \frac{N_1}{N_1 + N_2} \times 100\% \quad (2)$$

Note: Y means crushing length qualification rate, N_1 means crushing length less than 10 cm pieces, N_2 means crushing length greater than 10 cm pieces.

2.4. Test Data Statistics

Based on the results of the parameter optimization test, a regression model was established using regression analysis, and the accuracy of the model was evaluated by ANOVA analysis and lack-of-fit term analysis. Both the parameter optimization test and the operational performance comparison test used LSD to determine whether there was a

significant difference between the different levels, and ANOVA to determine whether the test factors had a significant effect on the test index. All data were processed and analyzed using MATLAB and Design-expert software, and plotted using Origin software.

3. Results

3.1. Parameter Optimization Test Results

As shown in Figure 4a,b, under the condition of fixed rotation radius, the cutting energy consumption first decreases and then increases as the output rotation speed accelerates, while the crushing length qualification rate becomes a gradually increasing trend, and the increasing trend gradually decreases. As shown in Figure 4c,d, under the condition of the fixed output rotation speed, the cutting energy consumption decreases and then rises with the increase of the rotation radius, while the crushing length qualification rate realizes a gradually rising trend, and the rising trend gradually decreases. The regression models between the two test factors and the two test indicators were derived separately using Design-Expert software (Equations (3) and (4)). As shown in Table 3, all parameters in the two regression models (R (Blade rotation radius), ω (Blade rotation speed), $R\omega$, R^2 , ω^2) have significant effects on the cutting energy consumption and crushing length qualification rate. Meanwhile, the p -values of the lack-of-fit term test for both regression models were greater than 0.1.

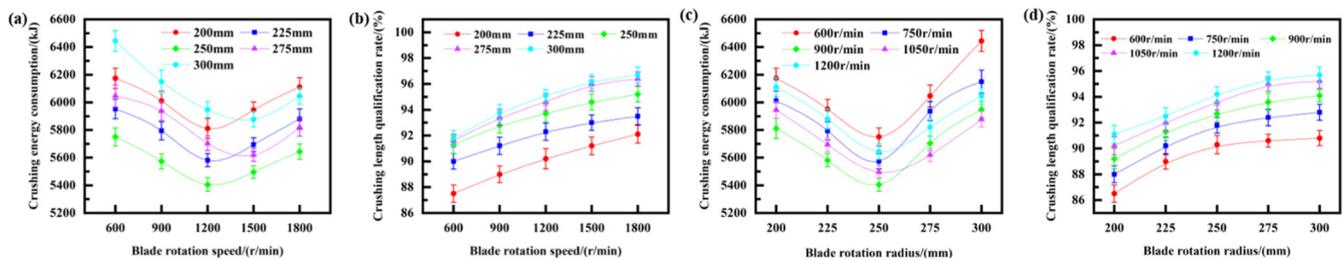


Figure 4. Parameter optimization test results. (a) Effect of blade rotation speed on cutting energy consumption. (b) Effect of blade rotation speed on crushing length qualification rate. (c) Effect of blade rotation radius on cutting energy consumption. (d) Effect of blade rotation radius on crushing length qualification rate.

Table 3. Test data.

Resources	Regression Model on Crushing Energy Consumption (Equation (3))				Regression Model on Crushing Length Qualification Rate (Equation (4))			
	Sum of Squares	df	F-Value	p-Value	Sum of Squares	df	F-Value	p-Value
Model	2.05×10^6	5	86.32	<0.0001 **	138.80	5	584.39	<0.0001 **
R	22,285.06	1	30.34	0.0389 *	58.75	1	1236.85	<0.0001 **
ω	1.41×10^5	1	4.80	<0.0001 **	70.09	1	1475.57	<0.0001 **
$R\omega$	53,592.95	1	11.54	0.0025 **	0.25	1	5.26	0.0312
R^2	9.35×10^5	1	106.35	<0.0001 **	1.84	1	38.71	<0.0001 **
ω^2	4.94×10^5	1	201.24	<0.0001 **	6.47	1	136.11	<0.0001 **
Residual	1.07×10^5	23	/	/	1.09	23	/	/
Lack of fit	96,392.45	19	1.94	0.2746	1.00	19	2.29	0.2196
Pure error	10,455.22	4	/	/	0.092	4	/	/
Cor total	2.11×10^6	28	/	/	139.89	28	/	/

Note: ** indicates highly significant ($p < 0.01$), * indicates significant ($0.01 < p < 0.05$).

The above experimental results show that the two regression models can provide accurate estimates of the optimal values of the two design parameters. Using MATLAB software, the minimum crushing energy consumption/acre under the condition that the crushing length qualification rate is greater than 95% is used as the solution condition.

The optimal combination of operating parameters of the machine was obtained as follows: when the blade shaft rotation speed is 930 r/min and the blade rotation radius is 248 mm, the estimated crushing length qualification rate can reach 92.89% and the crushing energy consumption can reach 5431.23 kJ.

$$Q = 5436.96 - 68.55\omega + 29.85R - 42.27R\omega + 165.00R^2 + 215.96\omega^2 \quad (3)$$

$$Y = 92.78 + 2.168\omega - 2.368R + 0.21R\omega - 0.601R^2 - 1.126\omega^2 \quad (4)$$

3.2. Performance Verification Test Results of Bionic Straw Returning Machine

As shown in Figure 5a–d, when the straw is returned in the same amount, the crushing energy consumption from largest to smallest is TB + TD > BB + TD > TB + TD > BB + BD. As shown in Figure 5e–h, when the straw is returned in the same amount, the crushing length qualification rate from high to low is: BB + BD > TB + BD > BB + TD > TB + TD.

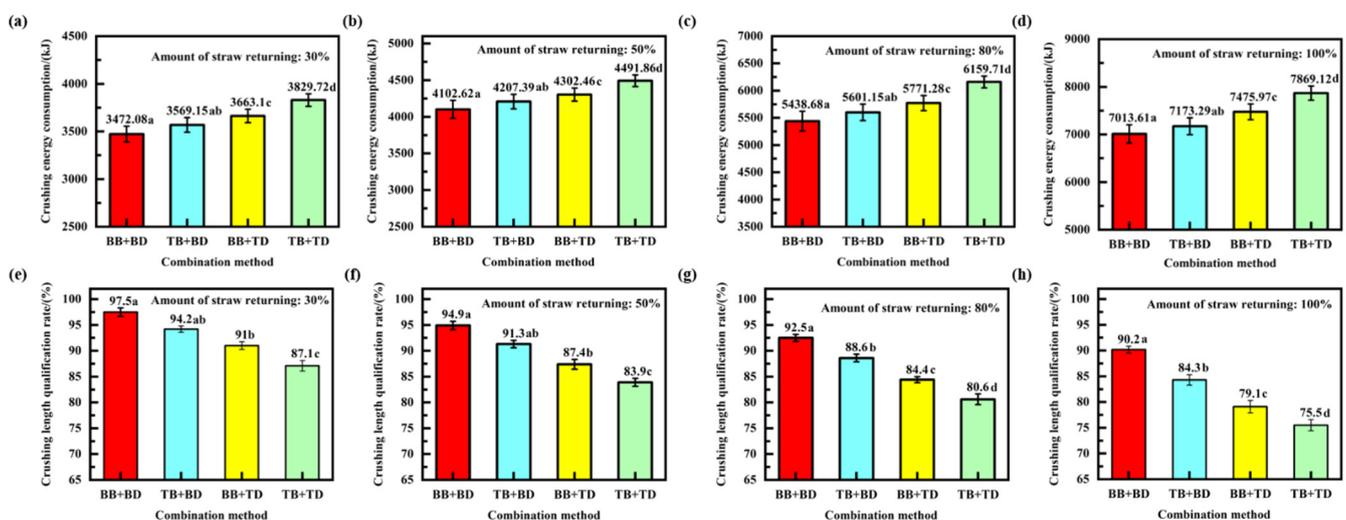


Figure 5. Parameter optimization test results. (a) Effect of different mechanism collocation methods on operating power consumption at 30% of straw returning amount. (b) Effect of different mechanism collocation methods on operating power consumption at 50% of straw returning amount. (c) Effect of different mechanism collocation methods on operating power consumption at 80% of straw returning amount. (d) Effect of different mechanism collocation methods on operating power consumption at 100% of straw returning amount. (e) Effect of different mechanism collocation methods on crushing length qualification rate at 30% of straw returning amount. (f) Effect of different mechanism collocation methods on crushing length qualification rate at 50% of straw returning amount. (g) Effect of different mechanism collocation methods on crushing length qualification rate at 80% of straw returning amount. (h) Effect of different mechanism collocation methods on crushing length qualification rate at 100% of straw returning amount. Averages followed by different lowercase letters are significantly different according to LSD's multiple range experiment at the significance level of 0.05. Error bars are standard deviation.

When the amount of straw returning is 30%, compared with TB + TD, BB + BD, TB + BD and BB + TD improve the crushing length qualification rate by 10.4%, 7.1% and 3.9%, respectively, and reduce the crushing energy consumption by 9.4%, 6.8% and 4.4%. When the amount of straw returning is 50%, compared with TB + TD, BB + BD, TB + BD and BB + TD improve the crushing length qualification rate by 11%, 7.4% and 3.5%, respectively, and reduce the crushing energy consumption by 9.5%, 6.3% and 4.2%. When the amount of straw returning is 80%, compared with TB + TD, BB + BD, TB + BD and BB + TD improve the crushing length qualification rate by 11.9%, 8% and 3.8%, respectively, and reduce the crushing energy consumption by 11.7%, 9.1% and 6.3%. When the amount of straw returning is 100%, compared with TB + TD, BB + BD, TB + BD and BB + TD improve the crushing length qualification rate by 14.7%, 8.8% and 3.6%, respectively, and reduce the crushing length consumption by 10.9%, 8.8% and 5.0%.

The above experimental results show that both the bionic blade structure and the bionic drive method can reduce the crushing energy consumption and improve the crushing length qualification rate, and the effect is more significant as the amount of straw returning increases. Compared with the bionic blade structure, the bionic drive method has a more significant effect on the improvement of operating performance.

4. Discussion

4.1. Discussion on the Law of Influence of Design Parameters on Operational Performance

The crushing length qualification rate of the straw returning machine depends mainly on the crushing success rate and the number of cutting times [35]. Maize straw can be cut off only when the driving force of the blade is greater than the cutting resistance [36]. Obviously, when the driving force of the blade is the same, the lower the cutting resistance, the higher the crushing success rate. Under the condition of the same crushing success rate, the more the number of cutting times, the higher the qualification rate of crushing length. Numerous studies have shown that the maximum cutting resistance is inversely proportional to the cutting linear speed of the blade [37]. From Equation (5), it can be seen that the larger the rotation radius R and output rotation speed ω , the larger the cutting linear speed of the blade. The higher the output rotation speed, the more times the straw is cut. Therefore, the crushing length qualification rate showed a gradual increase with increasing the rotation radius and output rotation speed. This is similar to the findings of He et al. in the maize-growing region of central China [17].

$$V_c = \omega R \frac{R-h}{R} \pm V = \omega R - \omega h \pm V \quad (5)$$

Note: V_c means cutting linear velocity, ω means output rotation speed, R means rotation radius, h means blade entry depth, V means Forward speed of bench test vehicle.

The crushing energy consumption Q of the bionic straw returning machine mainly includes the energy consumption Q_1 means the energy consumption generated by cutting straw Q_2 generated by disturbing soil. Lu et al. showed that Q_1 mainly depends on the cutting resistance, and the smaller the cutting resistance the lower the Q_1 [38]. Ma et al. showed that Q_2 mainly depends on the cutting pitch and the entry depth, and the deeper the entry depth or the shorter the cutting pitch the greater the Q_2 [39]. From the previous discussion, it is clear that the larger the rotation radius R and the output rotation speed, the smaller the Q_1 . From Equation (6), the larger the rotation radius R and output rotation speed ω , the smaller the cutting pitch. Therefore, the larger the rotation radius R and output rotation speed ω , the greater the energy consumption Q_2 for cutting the soil. Since the entry depth (90 mm) of the straw returning operation is small, the soil is less disturbed by the bionic straw returning machine when the cutting pitch is larger, and the magnitude of Q_1 is larger than Q_2 at this time. Therefore, when the rotation radius R and the output rotation speed ω are small, Q decreases as both increase. However, when the cutting pitch is small, the amount of soil disturbance by the bionic straw returning machine is larger, and the magnitude of Q_2 exceeds Q_1 at this time. Therefore, at a larger rotation radius R and output rotation speed, Q realizes a gradual increase as both increase.

$$\left[\begin{array}{l} Q = Q_1 + Q_2 \\ S = \frac{3000\omega^2(R-h)}{\pi Z} \end{array} \right] \quad (6)$$

Note: Q means crushing energy consumption, Q_1 means energy consumption generated by crushing straw, Q_2 means energy consumption from soil disturbance, S means cutting pitch, ω means output rotation speed, R means rotation radius, h means blade entry depth, Z means Number of bionic straw returning blades.

4.2. A Discussion on the Impact of Bionic Design on Operational Performance

Maize straw consists of the epidermis and pith [40]. The epidermis is composed of plant fibers, the pith is composed of lignin and spongy mesophyll [21]. Zhao et al. showed that the resistance generated by cutting the epidermis accounted for more than 90% of the total cutting resistance [41]. Zhao et al. showed that the straw epidermis was in a pulled-up state before the blade pierced the straw epidermis [21]. As the tensile deformation of the epidermis gradually increases, the tensile stress σ of the fiber gradually increases, resulting in a continuous increase in cutting resistance [42]. The maximum value of cutting resistance occurs at the moment when the straw epidermis is pierced [42]. Obviously, the longer it takes for the blade to pierce the straw epidermis, the greater the deformation generated by the straw epidermis and the greater the maximum cutting resistance. As shown in Figure 6, the contact area between the bionic blade structure and the straw epidermis is smaller compared to the traditional returning blade. As a result, the bionic blade structure produces less cutting resistance and allows for a higher straw crushing length qualification rate. Compared with the traditional blade structure, the bionic blade structure will significantly reduce the energy consumption of straw crushing energy operation Q_1 , and thus reduce the total energy consumption of returning operations.

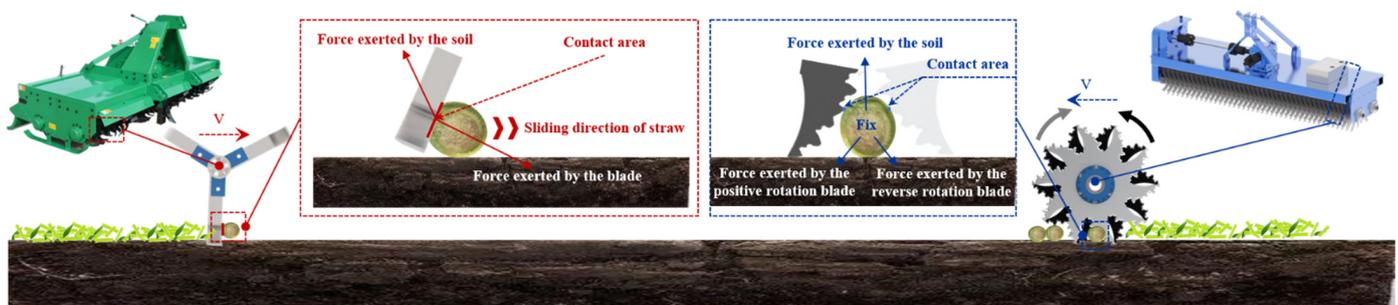


Figure 6. Comparison of the operating principle between traditional straw returning machine and bionic straw returning machine. The straw slips during the operation of traditional straw returning machine, and the contact area between the blade and the straw is large. During the operation of the bionic straw returning machine, the straw is fixed and the contact area between the blade and the straw is smaller.

As shown in Figure 6, when adopting the bionic drive method, the straw can realize the force balance under the joint action of forward and reverse rotation return blades and soil, and the cutting method at this time belongs to fixed cutting. When adopting the traditional driving method only one side of the straw is stressed in the horizontal direction, and the straw will move in the horizontal direction, and the cutting method at this time belongs to dynamic cutting. Numerous studies have shown that the operational resistance of fixed cutting is much lower than dynamic cutting [17]. Therefore, the bionic drive method produces less cutting resistance and can obtain higher straw crushing length qualification rate. The traditional driving method will throw the straw up and also cause the straw to translate on the soil surface, thus generating frictional energy and potential energy consumption. Therefore, the bionic drive method can significantly reduce the energy consumption of the straw returning operation compared to the traditional drive method.

In recent years, many scholars in the field of agricultural machinery engineering have conducted a large number of studies on methods to improve the operation performance of straw returning machines, but have focused more on the optimization of design parameters or operational parameters of existing machines [8,10–13,15]. The bionic straw returning machine developed by coupled bionic design with primnoa as the bionic prototype in this paper has made significant improvements in the cutting edge structure and cutting motion, thus improving the quality of straw returning operation more significantly than the previous studies.

5. Conclusions

In this paper, we found that the efficient gnawing ability of the primnoas on maize rootstocks was due to the segmented serrated structure of their mouthparts and the isokinetic reverse rotational movement. In this paper, we found that the blade rotation radius and the drive mechanism output rotation speed had a significant effect on the crushing energy consumption and crushing length qualification rate of the bionic straw returning machine. The optimized combination of design parameter values most suitable for the maize production region in northeast China should be 930 r/min and 248 mm. In this paper, it was found that the bionic blade structure is easier to pierce the epidermal skin of maize straw, thus reducing the cutting resistance. The bionic drive method can transform the cutting method of straw returning operation into fixed cutting, which effectively limits the displacement of straw during the cutting process while reducing the cutting resistance. The findings of this paper showed that the bionic straw returning machine can improve the straw crushing length qualification rate by 10.4–14.7% and reduce the straw cutting energy consumption by 9.4–11.7% compared with the traditional straw returning machine. The findings of this paper showed that the coupled bionic design can replicate the efficient cutting ability of the primnoa mouthpart to the straw returning machine. Therefore, this design method can be an effective means to provide future agricultural machinery design field.

It should also be noted that the current fuel cost of straw returning operations in the main maize-growing regions of northeast China is about 30 RMB/acre, and the bionic straw returning machine can reduce power consumption by up to 10.4–14.7%, thus potentially reducing that cost to 25.59–26.88 RMB/acre. The improvement of the straw crushing length qualification rate will also reduce the difficulty of sowing operations, which will lead to an increase in production and also bring greater economic benefits.

There are two limitations to the findings of this paper. First, the findings of this paper are mainly applicable to the main maize producing regions in northeast China, and the applicability to other regions or other crops needs further in-depth study. Secondly, due to the more severe epidemic situation at present, large-scale field trials were not conducted in this paper, but soil bin tests were used instead of field trials, so the findings of this paper may not fully reflect the influence of field environment on the operating effect of the machine.

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References

1. Sun, B.J.; Jia, S.X.; Zhang, S.X.; McLaughlin, N.; Zhang, X.P.; Liang, A.Z.; Chen, X.W.; Wei, S.C.; Liu, S.Y. Tillage, seasonal and depths effects on soil microbial properties in black soil of Northeast China. *Soil Till. Res.* **2016**, *155*, 421–428. [[CrossRef](#)]
2. Zhang, S.X.; Chen, X.W.; Jia, S.X.; Liang, A.Z.; Zhang, X.P.; Yang, X.M.; Wei, S.C.; Sun, B.J.; Huang, D.D.; Zhou, G.Y. The potential mechanism of long-term conservation tillage effects on maize yield in the black soil of Northeast China. *Soil Till. Res.* **2015**, *154*, 84–90. [[CrossRef](#)]

3. Liang, A.Z.; Yang, X.M.; Zhang, X.P.; Chen, X.W.; Mclaughlin, N.B.; Wei, S.C.; Zhang, Y.; Jia, S.X.; Zhang, S.X. Changes in soil organic carbon stocks under 10-year conservation tillage on a Black soil in Northeast China. *J. Agr. Sci.* **2016**, *154*, 1425–1436. [[CrossRef](#)]
4. Feng, H.Y.; Li, Q.Y.; Sun, L.Y.; Cai, Q.G. Using Cs-137 to study spatial patterns of soil erosion and soil organic carbon (SOC) in an agricultural catchment of the typical black soil region, Northeast China. *J. Environ. Radioact.* **2012**, *112*, 125–132. [[CrossRef](#)]
5. Li, H.Q.; Yao, Y.F.; Zhang, X.J.; Zhu, H.S.; Wei, X.R. Changes in soil physical and hydraulic properties following the conversion of forest to cropland in the black soil region of North-east China. *CATENA* **2021**, *198*, 104986. [[CrossRef](#)]
6. Wang, J.W.; Tang, H.; Wang, J.F. Comprehensive Utilization Status and Development Analysis of Crop Straw Resource in Northeast China. *Trans. CSAM* **2017**, *48*, 1–21.
7. Cheng, S.L.; Fang, H.J.; Zhu, T.H.; Zheng, J.J.; Yang, X.M.; Zhang, X.P.; Yu, G.R. Effects of soil erosion and deposition on soil organic carbon dynamics at a sloping field in Black Soil region, North-east China. *Soil Sci. Plant Nutr.* **2012**, *56*, 521–529. [[CrossRef](#)]
8. Zhao, J.L.; Lu, Y.; Tian, H.L.; Jia, H.L.; Guo, M.Z. Effects of Straw Returning and Residue Cleaner on the Soil Moisture Content, Soil Temperature, and Maize Emergence Rate in China's Three Major Maize Producing Areas. *Sustainability* **2019**, *11*, 5796. [[CrossRef](#)]
9. Horning, L.B.; Strtler, L.D.; Saxton, K.E. Surface residue and soil toughness for wind erosion protection. *Trans. ASAE* **1998**, *41*, 1061–1065. [[CrossRef](#)]
10. Zhou, H.; Zhang, J.M.; Xia, J.F.; Tahir, H.M.; Zhu, Y.H.; Zhang, C.L. Effects of subsoiling on working quality and total power consumption for high stubble straw returning machine. *Int. J. Agric. Biol. Eng.* **2019**, *12*, 56–62. [[CrossRef](#)]
11. Bao, X.B.; Zhao, X.Y.; He, J.; Li, H.W.; Wang, Q.J.; Liu, W.Z. Design and performance test of plowing and rotaty tillage combined machine. *INMATEH Agric. Eng.* **2019**, *58*, 213–222.
12. Wang, W.W.; Li, J.C.; Chen, L.Q.; Qi, H.J.; Liang, X.T. Effects of key parameters of straw chopping device on qualified rate, non-uniformity and power consumption. *Int. J. Agric. Biol. Eng.* **2018**, *11*, 122–128. [[CrossRef](#)]
13. Yin, X.G.; Olesen, J.E.; Wang, M.; Ozturk, I.; Chen, F. Climate effects on crop yields in the Northeast Farming Region of China during 1961–2010. *J. Agr. Sci.* **2016**, *154*, 1190–1208. [[CrossRef](#)]
14. Zhang, T.; Zhao, M.Q.; Liu, F.; Tian, H.Q.; Wulan, T.Y.; Yue, Y.; Li, D.P. A Discrete Element Method Model of Corn Stalk and Its Mechanical Characteristic Parameters. *Bioresources* **2020**, *15*, 9337–9350. [[CrossRef](#)]
15. Liao, N.; Han, L.J.; Huang, G.Q.; Chen, L.J.; He, C. Effects of moisture content and compression frequency on straw open compression energy consumption. *Trans. CSAE* **2011**, *27* (Suppl. S1), 318–322, (In Chinese with English Abstract).
16. Yu, C.Y.; Liu, J.; Zhang, J.; Xue, K.; Zhang, S.; Liao, J.; Tai, Q.L.; Zhu, D.Q. Design and optimization and experimental verification of a segmented double-helix blade roller for straw returning cultivators. *J. Chin. Inst. Eng.* **2021**, *44*, 379–387. [[CrossRef](#)]
17. Zheng, Z.Q.; He, J.; Li, H.W.; Diao, P.S.; Wang, Q.J.; Zhang, X.C. Design and Experiment of Straw-chopping Device with Chopping and Fixed Knife Supported Slide Cutting. *Trans. CSAM* **2016**, *47*, 108–116.
18. Shen, Y.; Zhang, T.; Cui, J.; Chen, S.; Han, H.; Ning, T. Subsoiling increases aggregate-associated organic carbon, dry matter, and maize yield on the North China Plain. *PeerJ* **2021**, *9*, e11099. [[CrossRef](#)]
19. Zhang, C. Study on the Dynamic of Soil Organic Carbon Accumulation and Maize Production in Long Term Straw Returning. Master's Thesis, Gansu Agricultural University, Lanzhou, China, 2017.
20. Ren, L.Q.; Liang, Y.H. Biological couplings: Classification and characteristic rules. *Sci. China Ser. E Technol. Sci.* **2009**, *52*, 2791–2800. [[CrossRef](#)]
21. Zhao, J.L.; Guo, M.Z.; Lu, Y.; Huang, D.Y. Design of bionic locust mouthparts stubble cutting device. *Int. J. Agric. Biol. Eng.* **2020**, *13*, 20–28. [[CrossRef](#)]
22. Jia, H.L.; Li, C.Y.; Zhang, Z.H.; Wang, G. Design of Bionic Saw Blade for Corn Stalk Cutting. *J. Bionic. Eng.* **2013**, *10*, 497–505. [[CrossRef](#)]
23. Liang, Y.C. Design and Test of Combined Straw and Stubble Crushing and Returning Machine. Master's Thesis, Shandong University of Technology, Zibo, China, 2020.
24. Wiedermann, A.; Harms, H.H. Straw-cutting machine Investigations on combine harvester straw-cutting machine with exact reaping. In Proceedings of the Conference on Agricultural Engineering, Limenas Heronissou, Greece, 23–25 June 2008; Volume 2045, pp. 257–262.
25. Li, C.Y. Bionic Blade of Corn Harvester for Leaving High Stubble and Its Cutting Mechanism. Ph.D. Thesis, Jilin University, Changchun, China, 2014.
26. Hu, J.P.; Zhao, J.; Pan, H.R.; Liu, W.; Zhao, X.S. Prediction Model of double axis rotary power consumption based on discrete element method. *Trans. CSAM* **2020**, *51*, 9–16.
27. Zhao, S.H.; Liu, H.P.; Yang, C.; Yang, L.L.; Gao, L.L.; Yang, Y.Q. Design and discrete element simulation of interactive layered subsoiler with maize straw returned to field. *Trans. CSAM* **2021**, *52*, 75–87.
28. Lin, J.; Qian, W.; Niu, J. Design and Experiment of Stubble-cutting and Anti-blocking Mechanism for Ridge-till and No-till Planter. *J. Shenyang Agric. Univ.* **2015**, *46*, 691–698.
29. Pei, Y.; Bian, S.F.; He, Z.; Cao, Y.; Ma, X.; Yu, J.Q. Study on a New Tilling Method of Striped Deep Loosening of Wide-Narrow Row Alternate Planting and Its Attached Machines. *Trans. CSAE* **2020**, *5*, 67–70.
30. Wang, F.L.; Dong, Z.G.; Wu, Z.H.; Fang, K. Optimization of maize planting density and fertilizer application rate based on BP neural network. *Trans. CSAE* **2017**, *33*, 92–99. (In Chinese with English abstract)

31. Inner Mongolia Province National Bureau of Statistics. In *China Statistical Yearbook*; China Statistical Publishing House: Beijing, China, 2020.
32. Heilongjiang Province National Bureau of Statistics. In *China Statistical Yearbook*; China Statistical Publishing House: Beijing, China, 2020.
33. Jilin Province National Bureau of Statistics. In *China Statistical Yearbook*; China Statistical Publishing House: Beijing, China, 2020.
34. Chen, L.Q.; Liang, X.T.; Cao, C.M. Virtual Simulation and Power Test of Straw Counters-field Based on Multi-body Dynamics. *Trans. CSAM* **2016**, *47*, 106–111.
35. He, J.; Zhang, Z.Q.; Li, H.W.; Wang, Q.J. Development of small/medium size no-till and minimum-till seeders in Asia: A review. *Int. J. Agric. Biol. Eng.* **2014**, *7*, 1–12.
36. Liao, Q.X.; Gao, H.W.; Shu, C.X. Design of sawing anti-blocking mechanism for no-tillage planter and its cutting mechanism. *Trans. CSAE* **2003**, *5*, 64–70.
37. Igathinathane, C.; Womac, A.R.; Sokhansanj, S. Corn stalk orientation effect on mechanical cutting. *Biosyst. Eng.* **2010**, *107*, 97–106. [[CrossRef](#)]
38. Lu, C.Y.; He, J.; Li, H.W.; Wang, Q.J.; Zhang, X.C.; Liu, J.A. Finite Element Analysis and Experiment on Anti-blocking Device Based on Support Cutting. *Trans. CSAE* **2013**, *44*, 61–66.
39. Ma, H.L.; Gao, H.W.; Li, H.W.; Wei, S.Y. Experimental Study on Corn Stalk and Rootstalk Cutting by Driven Disc. *Trans. CSAE* **2007**, *5*, 47–50+54.
40. Maraldi, M.; Molari, L.; Regazzi, N.; Molari, G. Analysis of the parameters affecting the mechanical behaviour of straw bales under compression. *Biosyst. Eng.* **2017**, *160*, 179–193. [[CrossRef](#)]
41. Zhao, J.L.; Wang, X.G.; Zhuang, J.; Cong, Y.J.; Lu, Y.; Guo, M.Z. Fine-Crush Straw Returning Enhances Dry Matter Accumulation Rate of Maize Seedlings in Northeast China. *Agronomy* **2021**, *11*, 1144. [[CrossRef](#)]
42. Wu, H.X. Research and Simulated Analysis for Corn Stalk Harvesting Technology and Equipment. Ph.D. Thesis, Jilin University, Changchun, China, 2014.