Design and experiment of the bionic disc cutter for kenaf harvesters

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Abstract: Aiming to ease the cutting of kenaf stalks via bionics, the bionic disc cutter was designed. The upper jaw of the *Batocera horsfieldi* was used as a bionic prototype. Further, to explore its dynamic performance, an indoor multi-stalk cutting experimental bench was used to simulate the field operation process. A three-factor and two-level interaction orthogonal experiment was carried out; cutting speed, stalk conveying speed (machine forward speed), and blade type (ordinary disc cutter and bionic disc cutter) were used as experiment factors. The cutting pass rate and cutting specific energy consumption were selected as evaluation indexes. The range, variance, and fuzzy comprehensive evaluation analysis were carried out on the experiment results. Moreover, the main order factors affecting the bionic cutter performance were determined-blade type, conveying speed, the interaction between the cutter speed and conveying speed, and cutter speed. The optimal parameter combination scheme had a cutter speed of 1000 r/min, conveying speed of 0.4 m/s, and included bionic blades. Under this condition, the best index was the 92% cutting pass rate, with a specific energy consumption of 4.38 J/stalk. The variance analysis has shown that, with 95% confidence, the blade type has a rather significant influence on the comprehensive index. Additionally, the conveying speed also significantly influenced it, while other factors and interactions had no notable effect. The experimental comparison under the same working condition shows that the bionic blade has better cutting effect. This study provides a reference for the development of cutter and the selection of kenaf harvester operational parameters.

Keywords: kenaf harvester, bionic, disc cutter, orthogonal experiment, interaction
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1 Introduction

Kenaf, formally known as Hibiscus cannabinus, is a bast fiber plant[1-3]. Kenaf plant is 3-5 m high, while its stalk diameter is 13.22-33.34 mm[4]. Its skin fiber is characterized by relatively high toughness and strength, hygroscopicity, permeability, and antistatic performance. Kenaf can be used in many fields such as textile, paper making, munitions, chemical industry, and new materials. Kenaf is considered as a textile raw material with the most potential for development[5-8]. It is often regarded as a “futuristic” crop by the United States, Japan, and other countries[9]. China’s kenaf planting area and output are one of the highest in the world[10,11]. In the international market, kenaf fabric is one of China’s products with the most favorable characteristics and strong competitive advantages.

Harvesting is an important part of kenaf production. Since the kenaf plant is tall and stout, the fiber toughness and strength of kenaf bark are relatively high, and its xylem is relatively hard. Manual harvesting is labor-intensive, characterized by low production efficiency, and high costs. Hence, meeting the production requirements of a modern kenaf industry is relatively difficult. In recent years, due to the country’s emphasis on the mechanization of production of characteristic cash crops, the research on bast-fiber crops harvesting technology is continuously increasing. Zhang et al.[12,13] designed a double-action cutter device for the problems of low cutting efficiency and large impact inertia of single-action cutter in ramie harvester. The field test showed that the ideal cutting efficiency could be achieved by adjusting the cutting speed. Shen et al.[14] used the cutting test bench to further compare and study the influence of different structural parameters and motion parameters of single and double acting cutter on the effect, and determined the optimal parameter combination of the cutter. Zhou et al.[15,16] used the obtained constitutive model parameters of industrial hemp stalk material to carry out finite element analysis of industrial hemp stalk cutting based on Ansys software, which provided a reference for improving the cutting quality and blade life of industrial hemp stalk cutter. Some advanced control technology[17] is also promising to be introduced to enhance cutting efficiency in the future. However, the aforementioned investigations are mainly focused on the bast-fiber crops with smaller stalk diameter (Mean stalk diameter<15 mm) such as ramie, industrial hemp. There is no research on stalk cutting of kenaf with thicker stems (mean diameter up to 23 mm). Achieving low resistance and high-quality cutting of kenaf stalks is one of the key technical problems that require solving in the development of kenaf harvesting equipment.

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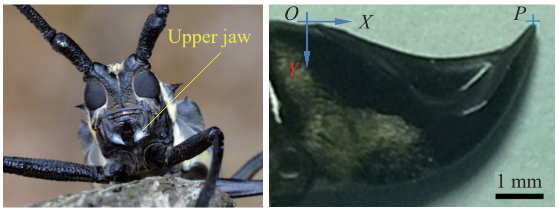
Bionics, as an interdisciplinary subject, provides an effective method for researchers to solve the energy consumption problem of cutter. Inspired by crickets eating tea stalks, Du et al.[18] designed a bionic blade with crickets teeth, and verified that the bionic blade has obvious drag and consumption reduction effect through experiments. Zhang et al.[19] designed a bionic blade based on the roof of the leaf cutter ant, aiming at the problems of poor sharpness and weak sliding performance of the grinding blade of silage corn harvester. Simulation and bench test show that the maximum cutting force of the bionic blade is obviously smaller than that of the contrast blade, and it has excellent cutting performance.

Aiming to ease the difficulty of bast fiber crops cutting, bionics principles were applied in the early stages. The *Batocera horsfieldi* (shown in Figure 1a), a pest with excellent bitting performance, was used as a bionic prototype. A reciprocating multi-tooth bionic blade was developed based on the structural characteristics of the upper *Batocera horsfieldi* jaw (shown in Figure 1b). Finally, a experiment was carried out to compare the cutting performance between bionic and ordinary blades (see Figure 2) for cutting industrial hemp. Experiments have shown that, compared to ordinary blades, the average maximum cutting force and cutting power consumption of bionic blades were reduced by 7.4% and 8.0%, respectively, while having a flatter stubble. Therefore, the bionic factors play an important and positive role in bast fiber crops cutting[20].



a. Batocera horsfieldi specimen b. Upper batocera horsfieldi jaw

Figure 1 *Batocera horsfieldi* and its upper jaw

a. Ordinary cutting blade b. Bionic blade

Figure 2 Comparison of two blades

To investigate the adaptability of the bionic blade to cutting kenaf stalks, experimental investigations of cutting kenaf stalks via the reciprocating multi-tooth bionic blade are conducted. Since the kenaf stalk is relatively thick, the required cutting force is relatively high. During the cutting process, the impact and vibration are severe, which easily leads to the bending failure of the cutter bar and the cutting jam, thereby indicating that the reciprocating cutter is no longer suitable for cutting the kenaf stalks. However, the advantages of low resistance and high-quality cutting of the bionic blade are still relatively important.

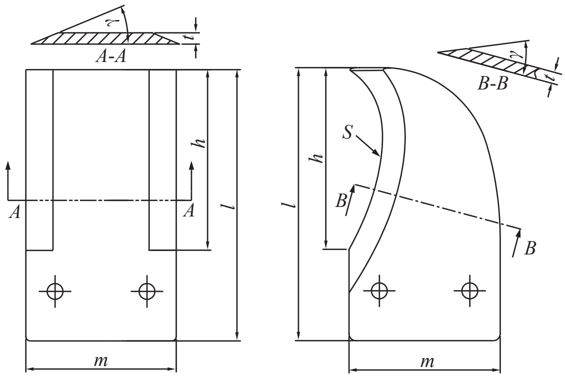
There are two main types of stalk crop cutters: reciprocating cutter and disc rotary cutters[21]. The latter are characterized by stable operation, small vibration, strong continuous operation ability, and high stubble quality[22,23] implying that they have notable advantages when cutting thick stalk crops[24,25]. Research on rotary disc cutter is as follows: Musa et al.[26] carried out kenaf cutting experiments with sawtooth disc cutter. The effect of cutting speed on cutting torque and cutting power of varying kenaf-stem diameters and at different moisture contents was investigated, the experiments showed that cutting speed was directly proportional to the specific cutting power, while the cutting torque was inversely proportional to the moisture content. Xue et al.[27] carried out cutting experiments on cassava stalk with a disc cutter cutting test bench, studied the effects of blade edge Angle, cutter Angle, cutter speed and machine forward speed on cutting force, and obtained the optimal combination of cutters. Deng et al.[28] developed a disc-type corn stalk cutting test-bed, simulated the cutting process of corn stalk through experiments, and obtained the combination of structure and motion parameters when the cutter played the best mechanical properties.

A new single-tooth bionic blade suitable for rotary cutting was designed to explore the advantages of bionics; the blade is closer to the bionic prototype. Next, the dynamic cutting performance comparison experiment between the new single-tooth bionic blade disc cutter and the common blade one was carried out. The indoor multi-stalk cutting experimental bench was used to determine the influence of the dynamic cutting parameters and their interactions on the cutting quality indicators. Moreover, the optimal blade type and cutter motion parameters were found, aiming to provide a reference for the development of kenaf cutters and the selection of harvester working parameters. Further, the study at hand is of great significance for both the energy-saving and emission reduction of harvesting machinery.

2 Design of bionic disc cutter

2.1 Structure design

Aiming to enable comparative analysis, the single-tooth bionic blade was made of the same blade material as the common blade (T9 steel). The heat treatment process (high-frequency rapid heating of nitrate isothermal quenching, quenching hardness HRC45-50) and blade matrix parameters (as shown in Figure 3a) were also the same. The blade length was l = 125 mm, cutting edge length h = 91 mm, blade thickness t = 5 mm, and blade angle γ = 23°.

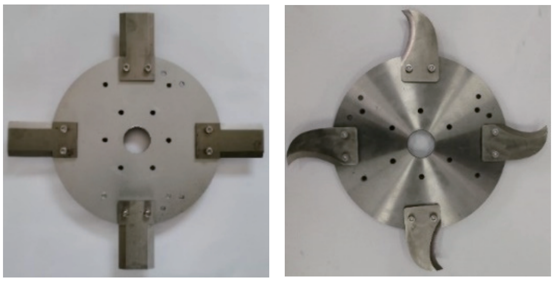


a. Ordinary blade b. Bionic blade

Figure 3 Schematic diagram of the both blades

The blade was designed and manufactured as follows: firstly, the fitting curve of the upper Batocera horsfieldi jaw[15] was enlarged. Its geometry was obtained in the previous study; the abscissa value is equal to the h value and is then used as the tooth edge S. Next, shapes of other blade parts are designed based on the tooth edge S. During the processing, laser cutting was used to cut out the blade shape. Finally, gear grinding machine was used to grind the blade surface. The structure diagram of the designed single-tooth bionic blade is shown in Figure 3b.

The disc cutter diameter was determined based on the kenaf planting row spacing, which is generally 35 cm[29]. When the harvester is working, two rows are cut by each disc cutter. The cutting allowance is 8 cm; hence, the disc cutter diameter can be calculated, equaling 43 cm. According to the maximum cutter diameter and the blade size, the disc size substrate can be obtained. The ordinary blade and the bionic blade disc cutter formed by assembling the disc and the cutter are shown in Figures 4a and 4b, respectively.

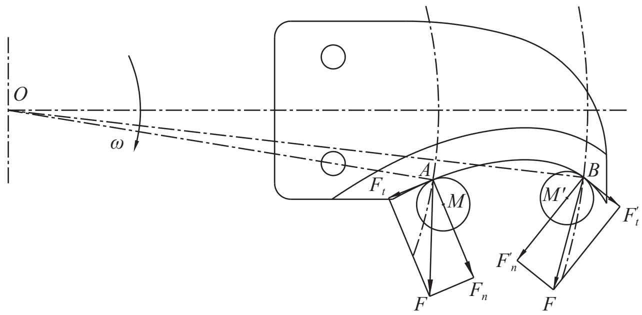


a. Ordinary cutter b. Bionic cutter

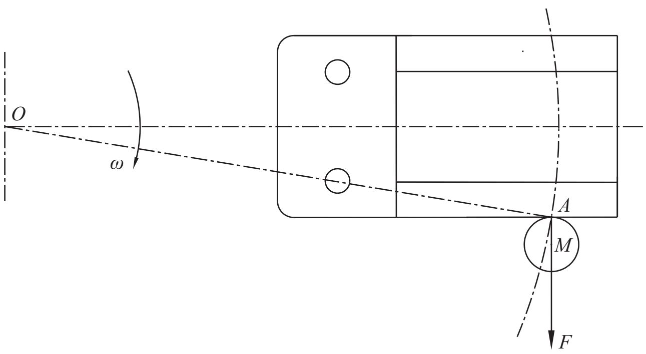
Figure 4 Disc cutter comparison

2.2 Force analysis

The graphic method was used to analyze the cutting force of the stalk by the bionic blade and the ordinary blade, the force analysis results are shown in Figure 5.



a. Analysis of cutting force of bionic blade



b. Analysis of cutting force of ordinary blade

Figure 5 Analysis of cutting force of different blades

As shown in Figure 5a, for the bionic blade, when the initial contact position of the stalk is on the left side of the blade, at the contact point A between the stalk and the blade, the stalk is subjected to the positive force of the blade, F_n, and the friction force of the blade on the stalk, F_t. The resultant force of F_n and F_t is F, and the direction points to the left of the stalk center point M, which is equivalent to applying a counterclockwise torque to the stalk with M as the center point. Since the root of the stalk is fixed, under the action of this torque, the upper stalk is forced to squeeze and slide to the right blade, which enhances the sliding cutting effect and reduces the cutting resistance.

When the initial contact position of the stalk is on the right side of the blade, at the contact point B between the stalk and the blade, the stalk is subjected to the positive force of the blade, F_n, and the friction force of the blade on the stalk, F_t. The resultant force of F_n and F_t is F, and the direction points to the right of the stalk center point M', which is equivalent to applying a clockwise torque to the stalk with M' as the center point. Under the action of this torque, the stalk is forced to squeeze and slide to the left blade, which also can enhances the sliding cutting effect and reduces the cutting resistance.

In addition, another important advantage is that during the cutting process, the concave arc curve on the right side of the bionic blade has a certain retention ability on the movement of the stalk, which can avoid the stalk sliding out of the cutting edge to the right, so it is conducive to cut off the stalk at once.

As shown in Figure 5b, for ordinary straight-edged blades, in the cutting process of the blade, the stalk only receives the normal force F perpendicular to the blade direction, and there is no slip-cutting effect, so the cutting resistance will increase.

3 Cutting experiment

3.1 Experimental materials

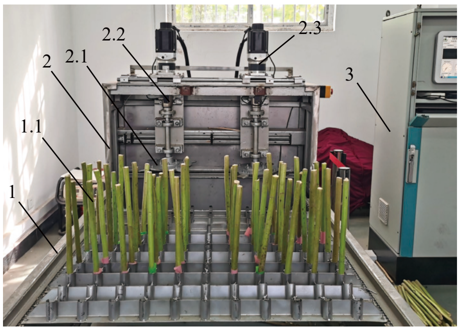
The kenaf stalk used in the experiment was collected in Nantong, Jiangsu Province. It was of the "Zhonghongma No.16" variety and was collected on September 21, 2022, during the kenaf harvest time (shown in Figure 6 and 7). Based on the field measurements, the average diameter of kenaf stalks was 23.25 mm at 10 cm above the ground (the blade cutting part). To quantitatively investigate the influence of blade types and motion parameters on the cutter performance, the kenaf stalks used in the experiment should be of the same size. In this experiment, the stalks with a diameter of (23±2) mm (10 cm above the ground) were selected uniformly. The cutting length was 40 cm from the ground to above. In order to prevent the material from denaturation due to the decrease of moisture content, the stalks were collected and sealed with plastic wrap, and transported to the laboratory for refrigeration within 5 h, and the experiment was completed within 1 week. At this time, the moisture content of the stalks was about 60%.

Figure 6 Kenaf plant exmaple

3.2 Experimental equipment

The experiment was carried out using the stalk cutting experimental bench developed by the research group. The experimental bench is composed of three parts-a cutting device, a conveying device, and a control system. Among them, the cutting device is equipped with a disc cutter, which is bolted to the driving spindle, enabling the cutter replacement. The conveying device was used to fix the stalks and convey them to the cutter, simulating the forward movement of the harvester. When clamping the kenaf stalk, its bottom was wrapped with a rubber sheet, fastening the kenaf stalking and preventing the stalk from leaving the fixture during the cutting. Additionally, such a solution also can avoid the rigid contact between the kenaf stalks and the fixture, which has a buffering effect. This simulates the kenaf stalk growth in the soil to the greatest extent. The measurement and control system components mounted on both the cutting and conveying devices are used to record, process, and output the cutting torque, power, and speed data. The overall experimental bench structure is shown in Figure 8.

Figure 7 Bottom of kenaf stalk



1. Conveying device 1.1. Stalks 2. Cutting device 2.1. Disc cutter 2.2. Torque transducer 2.3. Servo motor 3. Control system

Figure 8 Disc cutting experimental bench

The operation steps of the test bench are as follows: first, switch on the power, open the computer to enter the interface of the measurement and control system, input the cutter speed and conveying speed parameters, carry out no-load test run, and record the no-load energy consumption data by the data acquisition system. Stop the machine after the trial run, insert the industrial hemp stalk used in the test into the conveying device, set the cutter speed and conveying speed according to the test scheme sequence, all parameters are set, and the cutting test is carried out after ensuring safety. After the test, the test data automatically saved by the data acquisition system was exported and the results were analyzed.

3.3 Evaluation index

This experiment investigates the dynamic cutting performance of the bionic and the ordinary blade disc cutters. The cutting pass rate and specific energy consumption were used as evaluation indicators. The former is selected as the key index affecting the loss of harvester operation and is used to assess if it can work smoothly. The specific energy consumption directly reflected the advantages and disadvantages of the cutter's adaptability to kenaf stalk cutting. Additionally, it also directly affected machine energy consumption. Both evaluation indicators are important indexes to measure the cutter performance.

1) Cutting pass rate - the cutting pass rate is the ratio of the number of the completely cut kenaf stalks (the xylem and kenaf fiber are completely broken) and the length of residual kenaf skin at the incision was less than 5 cm to the total number of stalks involved in the cutting. It can be calculated as:

$$y_1 = \frac{N_1}{N} \times 100\% \tag{1}$$

where, y_1 is the cutting pass rate; N_1 is the number of the completely cut kenaf stalks; N is the total number of kenaf stalks participating in the cutting operation.

2) Specific energy consumption - the average energy consumed for cutting a single stalk. It is calculated as a difference between the energy consumed after completing a set of cutting experiments and the no-load energy consumption of the experimental bench. The result is then divided by the number of kenaf stalks participating in the cutting operation. The expression is written as:

$$y_2 = \frac{W - W_0}{N} \times 100\% \tag{2}$$

By expanding it, the following equation is obtained:

$$y_2 = \frac{\sum_{i=1}^{n} T_i \Delta\omega - \sum_{i=1}^{n} T_{i0} \Delta\omega}{N} \tag{3}$$

where, y_2 is the specific energy consumption, J/stalk; W is the total cutting experiment energy consumption, J; W_0 is the no-load experimental bench energy consumption, J; T_i is the ith data sampling point of the torque sensor during the cutting experiment (corresponding torque value), N·m; T_{i0} is the torque value corresponding to the ith sampling point of the experiment torque sensor when there is no load, N·m; $\Delta\omega$ is the torque sensor rotation angle at the time interval between two adjacent sampling points, (°).

3.4 Experimental factors and levels

3.4.1 Determining the experiment levels

The indoor multi-stalk experimental bench is used to simulate the field operation experiment. The involved motion parameters are the cutting speed and the conveying speed. According to the literatures[20,30], the circumferential speed of the disc cutter blade tip is generally 15-25 m/s. Since the diameter of the disc cutter blade tip designed in this experiment is 480 mm, the corresponding rotation speed was calculated as 597-995 r/min. To facilitate the experiment, 600-1000 r/min were used in this study.

Since the development of kenaf harvester remains in initial stages and there is no unified standard for its operational efficiency, this study will refer to the representative operating speed of the grain combine harvester. According to the literature[31], the operating speed of the semi-feeding self-propelled grain combine harvester is between 1.3 and 3.0 km/h, that is, 0.36 m/s to 0.83 m/s. Hence, in the experiment, the operating speed was 0.4-0.8 m/s. Each factor had two levels, and the resulting experiment factor level is listed in Table 1.

Table 1 Experimental factors and levels

Levels	Factors		
	Cutter speed A/r·min^{-1}	Conveying speed B/m·s^{-1}	Cutter type C
1	600	0.40	Ordinary cutter
2	1000	0.80	Bionic cutter

3.4.2 Experimental design

An orthogonal experiment was designed with three factors and two levels. The influence of interactions between the factors on the experiment index is not clear and was, therefore, was studied. When creating the orthogonal table, the interaction should be treated as a factor. Thus, the orthogonal table should be selected for six factors and two levels. The smallest orthogonal table that satisfies this condition is $L_8(2^7)$. According to the design rule for the $L_8(2^7)$ orthogonal table header with interaction[32], factors A, B, and C can be arranged in the first, second, and fourth columns respectively. The interactions $A\times B$, $A\times C$, and $B\times C$ are arranged in the 3rd, 5th, and 6th columns, respectively. Finally, the 7th column is denoted as the error column. The experimental design is listed in Table 2.

Table 2 Experimental scheme and results

No.	A	B	$A\times B$	C	$A\times C$	$B\times C$	Vacant	y_1/%	y_2/J·stalk^{-1}
1	1	1	1	1	1	1	1	70	4.49
2	1	1	1	2	2	2	2	82	3.76
3	1	2	2	1	1	2	2	72	4.77
4	1	2	2	2	2	1	1	82	4.36
5	2	1	2	1	2	1	2	86	5.48
6	2	1	2	2	1	2	1	92	4.38
7	2	2	1	1	2	2	1	74	5.56
8	2	2	1	2	1	1	2	84	4.43

The experiment was carried out according to the experiment plan table; a total of 25 stalks were cut for each experiment, and the experiments were repeated twice for each experiment run. Finally, the cutting pass rate and specific energy consumption index of each experiment run were evaluated separately, and the average value was taken.

3.5 Results and Analysis

Upon completing all experiments, statistical methods were applied to experimental results, which are listed in Table 2.

The range analysis was conducted on the experiment results (listed in Table 2) to determine the primary and secondary order of the influence of each experimental factor on the index. The analysis results are given in Table 3.

The larger the range, the greater the influence of the experiment factor level change on the index, as can be seen from the range analysis in Table 3.

1) For the cutting pass rate index y_1, the range order is $R_C>R_A>R_{A\times B}>R_B>R_{A\times C}>R_{B\times C}$. Hence, the primary and secondary order of the influence of each factor on the cutting pass rate is blade type C, cutter rotation speed A, the interaction between A and B, conveying speed B, the interaction between A and C, and finally, the interaction of B and C.

Table 3 Results of range analysis

Index		A	B	$A\times B$	C	$A\times C$	$B\times C$	Vacant
y_1	K_1	76.5	82.5	77.5	75.5	79.5	80.5	79.5
	K_2	84	78	83	85	81	80	81
	R	7.5	4.5	5.5	9.5	1.5	0.5	1.5
	Sequence of factors $C>A>A\times B>B>A\times C>B\times C$							
y_2	K_1	78.17	81.46	82.04	91.32	81.34	84.39	84.51
	K_2	89.32	86.03	85.45	76.17	86.15	83.10	82.98
	R	11.15	4.58	3.40	15.14	4.81	1.29	1.52
	Sequence of factors $C>A>B>A\times C>A\times B>B\times C$							

According to the primary and secondary order of factors, interaction $A\times B$ had a greater impact on the index than factor B. Therefore, when aiming to determine the optimal B level, interaction $A\times B$ should be considered; it was determined based on the collocation of each factor A and B level. The two-factor interaction collocation is listed in Table 4.

Table 4 Interaction collocation table

B	A	
	A_1	A_2
B_1	76	89
B_2	77	79

As listed in Table 4, the best combination between A and B is A_2B_1, meaning that the better A and B factor levels are A_2 and B_1. Combined with the range analysis results listed in Table 3, it can be concluded that the optimal factor level combination scheme when aiming to improve the cutting pass rate index is $A_2B_1C_2$.

2) For the specific energy consumption index y_2, the range order is $R_C>R_A>R_B>R_{A\times C}>R_{A\times B}>R_{B\times C}$. Hence, the primary and secondary order of the influence of each factor on the specific energy consumption is blade type C, cutter rotation speed A, conveying speed B, the interaction between A and C, the interaction between A and B, and lastly, the interaction between B and C. The interaction between any two factors is less influential than a single factor. Therefore, it can be ignored when selecting the optimal level collocation, which is, in this case, $A_1B_1C_2$.

Variance analysis was also conducted on the experiment results, which are listed in Table 5.

As can be seen from Table 5, in the cutting pass rate variance analysis, $MS_{A\times C}\leq MS_e$ and $MS_{B\times C}\leq MS_e$, indicating that the interactions $A\times C$ and $B\times C$ have a rather limited influence on the cutting pass rate. Similarly, in the specific energy consumption variance analysis, $MS_{B\times C}\leq MS_e$, indicating that the interaction $B\times C$ also has a limited effect on the contrast energy consumption. Both behaviors could be classified as errors, and then calculated to obtain a new error e^{Δ} and significance.

In Table 5, the left side of the "}" symbol represents the statistical result before the error correction, while the right side is the statistical result following the correction. Based on the analysis of variance after the error correction at a significance level $\alpha = 0.05$, various factors have different effects on the indicators. For the cutting pass rate index, the cutter speed A and blade type C had an extremely significant influence on the experiment results ($p\leq0.01$). Furthermore, the conveying speed B and the interaction $A\times B$ also had a significant influence ($0.01<p\leq0.05$), while the influence of interaction $B\times C$ was not significant ($p>0.05$). Regarding the specific energy consumption index, blade type had a significant influence on the experiment results ($p\leq0.01$), it was concluded that the cutter speed A had a significant influence ($0.01<p\leq0.05$) on the energy consumption index, and the conveying speed B, while interactions $A\times B$ and $A\times C$ were not significant ($p>0.05$).

3.6 Optimization of factors

Aiming to improve the cutting performance, the cutter should simultaneously have an high cutting pass rate and low specific energy consumption. Due to the variations in primary and secondary order, as well as the significance of the effects of various factors on experiment indexes, optimal parameter combinations have differed. Hence, to further analyze the influence of factors on the cutting quality, the comprehensive fuzzy evaluation method was used to both evaluate and analyze the experiment results[33-35]. The multi-index evaluation was transformed into the single-index evaluation and the parameter combination yielding optimal indexes was selected. The steps were as follows:

Table 5 Analysis of variance

Experiment index	Sources of variation	Sum of squares	df	Mean square	F value	Significant
y_1	A	112.5000	1	112.5000	35.5263	**
	B	40.5000	1	40.5000	12.7895	*
	$A\times B$	60.5000	1	60.5000	19.1053	*
	C	180.5000	1	180.5000	57.0000	**
	$A\times C$	4.5000	1	4.5000		
	$B\times C$	0.5000	1	0.5000		
	e	4.5000	1	4.5000		
	e^{Δ}	9.5000	3	3.1667		
	Sum	403.5000				
Experiment index	**Sources of variation**	**Sum of squares**	**df**	**Mean square**	**F value**	**Significant**
y_2	A	0.7626	1	0.7626	59.06	*
	B	0.1275	1	0.1275	9.8751	
	$A\times B$	0.0703	1	0.0703	5.4453	
	C	1.4196	1	1.4196	109.9409	**
	$A\times C$	0.1485	1	0.1485	11.5015	
	$B\times C$	0.0105	1	0.0105		
	e	0.0153	1	0.0153		
	e^{Δ}	0.0258	2	0.0129		
	Sum	2.5544				

Note: ** stands for high significance and * stands for significance.

Firstly, based on the indicator importance, the cutting pass rate and specific energy consumption weight values are determined as x_1 and x_2, respectively, constituting the weight distribution set $W=[x_1\,x_2]$. When designing the harvesting kenaf, priority should be given to ensure a high cutting pass rate. In other words, the cutting pass rate has priority relative to the cutting ratio energy consumption. Therefore, the weight allocated should be greater than the weight of the specific energy consumption. For this reason, $W=[0.6\ 0.4]$ was used in this experiment. Secondly, it was necessary to establish two index membership degree models to obtain the dimensionless membership degree values with the same order of magnitude. The larger the cutting pass rate index value - the better; the associated membership model is shown in Equation (4). Similarly, the smaller the cutting ratio energy consumption index value, the better, and its membership model is shown in Equation (5).

$$r_{1j}=\frac{\left(y_{1j}\right)_{\min}-y_{1j}}{\left(y_{1j}\right)_{\min}-\left(y_{1j}\right)_{\max}}(j=1,2,3\ldots8)\tag{4}$$

$$r_{2j}=\frac{\left(y_{2j}\right)_{\max}-y_{2j}}{\left(y_{2j}\right)_{\max}-\left(y_{2j}\right)_{\min}}(j=1,2,3\ldots8)\tag{5}$$

where, r_{1j} and r_{2j} are the membership values of indexes y_1 and y_2 measured during the jth experiment when the index is large and small, respectively. Furthermore, y_{1j} and y_{2j} are the values of the jth experiment indexes y_1 and y_2, respectively.

According to membership values r_{1j} and r_{2j} representing the cutting pass rate and specific energy consumption obtained by Equations (4) and (5), the index membership matrix R can be constructed:

$$R=\begin{pmatrix} r_{11} & r_{12} & \ldots & r_{1j} \\ r_{21} & r_{22} & \ldots & r_{2j} \end{pmatrix}\tag{6}$$

Further, using the expression $U = W{\cdot}R$, the comprehensive score U can be obtained for each experiment scheme. The higher the scheme score, the better its comprehensive cutting performance will be.

The calculated membership degree and comprehensive score values for each index are given in Table 6.

Table 6 Comprehensive score

Experiment No.	Membership values of r_{1j}	Membership values of r_{2j}	Score U
1	0	0.5944	0.2378
2	0.5455	1	0.7273
3	0.0909	0.4389	0.2301
4	0.5455	0.6667	0.594
5	0.7273	0.0444	0.4541
6	1	0.6556	0.8622
7	0.1818	0	0.1091
8	0.6364	0.6278	0.6330

The comprehensive score can be used as an indicator for performing a range analysis of the experiment results (for results see Table 7). It is also necessary to refer to the error correction method when aiming to perform the variance analysis on the comprehensive score results (see Table 8).

Table 7 Results of comprehensive evaluation range analysis table

Experiment index		A	B	$A\times B$	C	$A\times C$	$B\times C$	Vacant column
Comprehensive score U	K_1	0.4473	0.5703	0.4268	0.2578	0.4908	0.4798	0.4508
	K_2	0.5145	0.3915	0.5350	0.7040	0.4710	0.4820	0.5110
	R	0.0672	0.1788	0.1082	0.4462	0.0198	0.0022	0.0602
	Sequence of factors $C>B>A\times B>A>A\times C>B\times C$							

Table 8 Results of comprehensive evaluation analysis of variance table

Sources of variation	Sum of squares	Degrees of freedom	Mean square	F value	Significant
A	0.0091	1	0.0091	3.3681	
B	0.0639	1	0.0639	23.7735	*
$A\times B$	0.0235	1	0.0235	8.7220	
C	0.3985	1	0.3985	148.1528	**
$A\times C$	0.0008	1	0.0008		
$B\times C$	0.0000	1	0.0000		
e	0.0073	1	0.0073		
e^{Δ}	0.0081	3	0.0027		
Sum	0.5030				

According to the comprehensive score range analysis (Table 7), the primary and secondary actions affecting the comprehensive cutting performance were determined. They included blade type C, conveying speed B, the interaction between the cutter speed A and conveying speed B, and cutter speed A. Further, the interaction between the cutter speed A and blade type C was found, as well as the interaction between the conveying speed B and blade type C.

Based on the primary and secondary factor orders, interaction $A\times B$ has a greater impact on the index than factor A. Hence, to determine the optimal A level, $A\times B$ should be considered and determined according to the collocation of each level of factors A and B. The two-factor interaction collocation table is given in Table 9.

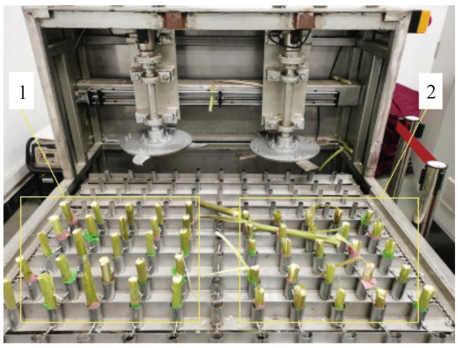
Table 9 Interaction collocation table

	A_1	A_2
B_1	0.4826	0.6582
B_2	0.4121	0.3711

As can be seen in Table 9, combination A_2B_1 was the best of the considered matches. Combined with the range analysis data provided in Table 7, it can be seen that for the comprehensive scoring index, the optimal factor level combination scheme is $A_2B_1C_2$. Said combination represents the cutter speed of 1000 r/min, 0.4 m/s conveying speed, and the application of bionic blades. This scheme combination corresponds to the No.6 experiment in the experiment scheme. When using this scheme combination, the cutting pass rate was 92%, while the specific energy consumption was 4.38 J/stalk.

Finally, it can be seen from the comprehensive score variance analysis (Table 8) that, with 95% confidence, the blade type has a very significant influence on the comprehensive experiment index ($p\leq0.01$). It should also be added that the conveying speed also has a significant influence on the comprehensive experiment index while the remaining factors and interactions have no effect.

The cutting effect of the two cutters under the same working condition is shown in Figure 9.



1. Stubbles of bionic disc cutter 2. Stubbles of ordinary disc cutter

Figure 9 Comparison of cutting effect

Under the working condition of the optimal scheme combination (i.e., the cutter speed is 1000 r/min and the conveying speed is 0.4 m/s), the cutting effect of the two blades is shown in Figure 9. It can be seen from Figure 9 that under the same working condition, the stubbles of kenaf stalks cut by the bionic cutter are relatively flat, while the stubbles of kenaf stalks cut by the ordinary cutter are generally broken or the flax skin are not cut off, and the cutting qualified rate is low. The comparison shows that the bionic cutter has better cutting effect.

4 Conclusions

1) Building on the previous research, a bionic disc cutter for kenaf was designed using the upper *Batocera horsfieldi* jaw as a bionic prototype. The force analysis of the cutting stalk by bionic blade and the common straight blade shows that the bionic blade has the effect of sliding cutting and reducing resistance.

2) Aiming to investigate the bionic disc cutter dynamic performance, the orthogonal experiment including the multi-stalk cutting was carried out. Further, the order of primary and secondary actions affecting the cutting pass rate and specific energy consumption indexes was determined. The indexes were determined as follows: blade type, conveying speed, the interaction between the cutter speed and the conveying speed, cutter speed, and interaction between the cutter speed and blade type. The lowest interaction value was between conveying speed and blade type. At a 95% confidence level, the blade type had a very significant effect on the comprehensive experiment index. Moreover, the conveying speed has a significant effect on the comprehensive experiment index, while other factors and interactions do not. The optimal plan combination is that the cutter speed is 1000 r/min, with the conveying speed of 0.4 m/s, and the blade type is a bionic blade. Using this plan combination, the cutting pass rate was 92%, with a specific energy consumption of 4.38 J/stalk.

3) Through the analysis of the experimental results, it can be seen that the blade type is the most important factor affecting the cutting pass rate, specific energy consumption, and comprehensive evaluation indexes. The application of a bionic blade can greatly improve the quality of stubble cutting and reduce the cutting resistance, which fully demonstrates the bionic blade has excellent applicability in cutting kenaf stalks. The research results will help promote the energy-saving and emission reduction of agricultural machinery, harvesting equipment, and has important application value.

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