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Design and Experiment of Profiling Furrow-Ridge Terrain by Cane Leaf-Chopping and Returning Machine

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Abstract: Conventional straw-returning machines were incompatible with ridge cultivation terrain and unevenly distributed materials, resulting in substandard operations such as insufficient leaf fragmentation, damage to ratoon stumps, and high cutting energy consumption. In this regard, this paper proposes a novel profiling configuration of chopping and returning machine to adapt to the coverage characteristics of cane leaves in furrow-ridge terrain. The leaves piled at furrow sole are intensively collected and fed into the whirling space by the flexible hook teeth assembly, and are cooperatively broken by the unequal-length swing blades densely arranged along the double helix. Based on the measured topographic trends and dynamic analysis of the leaf-shredding process, experimental factors affecting profiling cutting and picking capabilities of the main components were determined. Further, using chopping qualification rate (CQR) and fragmentation degree (CFD) as indicators, field trials were conducted through a response surface method to test the comprehensive crushing performance of the machine. After multi-objective optimization, the optimal structural and operating parameters were determined as: blade length gradient of 1.57 cm, teeth spacing of 6.84 cm and feed speed of 3.2 km/h. With such adaptive configurations, CQR and CFD reached 81.14% and 0.101, respectively, which were significantly improved by 60.50% and 47.99% compared to those of conventional machines. Crushed leaves appeared to be more thoroughly mixed with the soil and more evenly spread in the field. Meanwhile, the traction resistance tended to be stable, with an effective RSM 45.85% lower than the value of higher-level blade gradient, indicating a better overall fit with the irregular terrain. This study can provide a reference for the development of leaf-chopping and returning machines suitable for ridge-type crops.

Keywords: ridge topography; chopping of cane leaf; profiling blade arrangement; field terrain fit; operation resistance



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1. Introduction

Sugarcane is a perennial ridge-type crop grown in high-density clusters, and the cultivated fields have significantly undulating ridge row structures [1]. Since the sugar-making process requires the impurity content of sugarcane raw materials to be as low as possible, impurity removal processes such as cutting off leaf tips and peeling leaves are set up in the combined harvester. Large quantities of separated long cane leaves are thrown directly onto the field surface to cover [2]. During the operation, under the comprehensive influence of the exhaust airflow of the harvester, airflow from high-powered fans, and strong airflow in the northern hemisphere winter, the scattered sugarcane leaves will further move to low-lying furrows between ridges, forming non-uniform accumulation. If left on the ground, they may become entangled in rotary tillage tools involved in subsequent land preparation or farming, seriously reducing work efficiency and quality, and affecting the growth supply

of the next crop emergence [3]. Burning in fields is also prohibited. By mixing crushed leaves with soil and returning them to the fields, the nitrogen, phosphorus, and potassium in original cane leaves can be reused, enhancing soil fertility [4,5]. However, since the ability of microorganisms in the soil to decompose leaves is limited, the fragmentation degree of cut leaves determines the conversion efficiency of these elements [6].

The leaf choppers mainly use multiple knives to hit, tear, and rub straws or stem leaves until they are broken [7]. Since the height difference between furrows and ridges in sugarcane fields is very obvious under a wide row spacing of 1.2~1.6 m, in order to avoid damaging the buried ratoon stumps remaining in ridges, the chopper cannot cut into the soil layer for crushing, and the resulting cutting load would be too large for the machine to bear. Then, if the blade tips are aligned with the ridge top, as when using a conventional straw-returning machine, it lacks effective processing capabilities for most leaves piled in the furrow sole. Moreover, unlike corn or wheat leaves, cane leaf is generally longer and has more developed midribs, which contain large amounts of cellulose, hemicellulose, lignin, etc. [8]. Its strong toughness results in a greater energy required for complete shredding. To sum up, this puts forward higher requirements for leaf-chopping performance under the dual constraints on the tool-setting position.

As far as existing leaf-chopping machines are concerned, the available straw returning machine structures are still insufficient to adapt to the cultivation terrain and leaf material characteristics of ridge-type crops like sugarcane. This has led to prominent problems, such as substandard leaf fragmentation, visible stump damage, and high operating energy consumption when cutting into the ridge soil [9,10]. In terms of leaf pickup mechanism, Ye et al. [11] proposed an evaluation and applicable standard for bending angles of cane leaves to simulate and optimize the picking material retrieval process. Regarding kinematic control of field material conveyor, Lin et al. [12] and Guo et al. [13] both used spiral tool arrangement to realize the active directional movement of straw, and made targeted parameter improvements based on the returning and row-sorting requirements. For deep burial mixed with soil, Huang et al. [14] designed an integrated return machine with dual functions of crushing and rotary tillage, but fragmental quality was poor due to its incompatibility with sugarcane furrows. As for collaborative matching of machine tool operation parameters, Wu et al. [15] and Liu et al. [16] studied the effects of different combinations of cutter shaft speed, ground clearance and blade spacing on the crushing pass rate, throwing uniformity, and power consumption from various perspectives. In addition to these, faced with the wrapping of cutting mechanism by long tough sugarcane leaves, Qiu et al. [17] and Li et al. [18] designed an anti-wrapping blade roller with bent blades and a combined fixed-swinging blade arrangement to overcome possible blockage issue. In summary, the above-mentioned research progress on related machine models and key components is still unable to adapt to the processing conditions of leaves covered in staggered furrow-ridge terrain, and there is a lack of profiling cutting methods suitable for ratoon cane fields.

In view of shortcomings of conventional straw-returning machines used in sugarcane fields, such as insufficient crushing, damaged stumps and high cutting energy consumption, a chopper configuration that profiles irregular terrain is proposed to adapt to the leaf coverage characteristics between furrows and ridge rows. The structures of main blade arrangement and pick-up assembly were designed based on the measured topographic change trends. The key factors affecting their cutting and feeding capabilities were further determined through a dynamic analysis of chopping process. With the response surface method, field experiments were conducted to study the influence on the comprehensive crushing effect. After multi-objective optimization, the improved performance using optimal parameters was subsequently verified and compared with the original. The traction resistance characteristics were also used to evaluate the fit to field terrain, as well as energy consumption.

2. Materials and Methods

2.1. Working Conditions

2.1.1. Ridged Field Topography

After the harvest season, multiple acres of ratoon fields in Fusui County, Chongzuo City, Guangxi Province, a typical “double-high” standardized sugarcane planting area in South China, were selected as samples for topographic measurements. The original variety planted here was the widely used Guitang No. 42, which generally had a stalk height ranging from 2.5 to 3.1 m. The planting row spacing between ridges was mechanically tilled and measured to be 1.2 m. The appearance of stripped leaves covering the field is shown in Figure 1. The terrain contour can be seen to have distinct undulations between furrows and ridges. Lots of cane leaves over 1.0 m long were spread across the field, but most of them were mainly accumulated inside the furrow area.

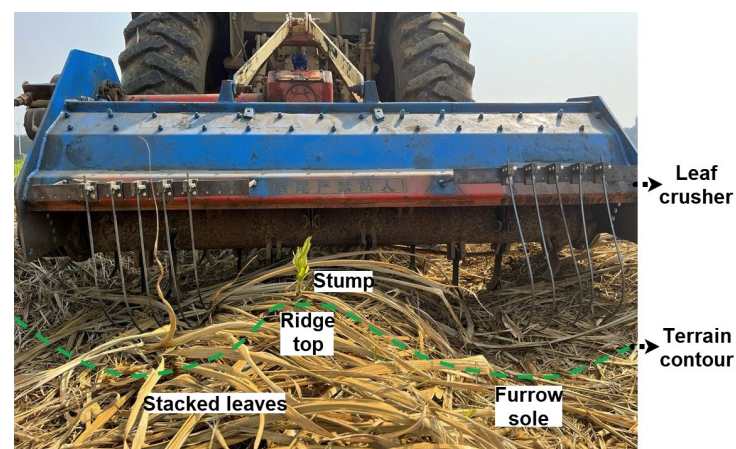


Figure 1. Sugarcane field terrain and covered leaf materials.

Since there are certain differences in the ridge shapes and specifications of different plots or rows, the topographic fluctuation change model obtained by collecting multiple acres of surface data is shown in Figure 2, in which the upper and lower boundaries and the average profile curve are illustrated. It has been measured that the height difference from ridge top to furrow sole is ~8.9–15.5 mm. Under the large working width, larger than double rows required for high efficiency, it is difficult to use linearly arranged blades to hit the sunken leaves without cutting into the ridge. In addition, the lateral distance of a single furrow-ridge structure also has a slope-related error of less than 150 mm, which should be fully accommodated in the profiling arrangement of blades to match such an enclosed terrain deviation area. Subsequent cutting reference lines determined in this area should maximize the fit of terrain trends on the basis of avoiding injuries to top stumps.

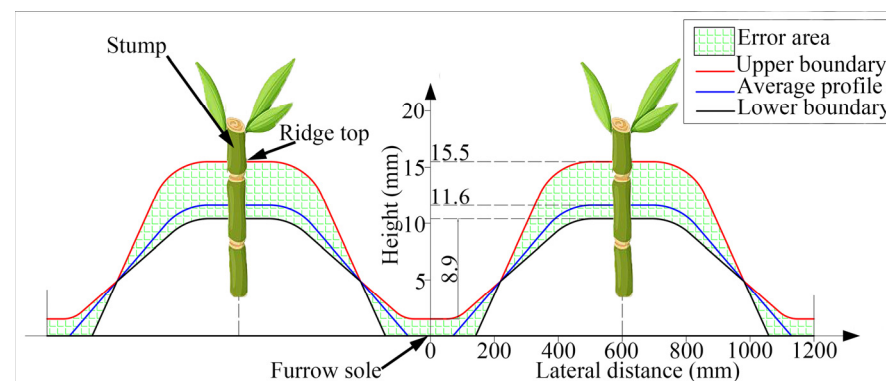


Figure 2. Fluctuating changes in topographic contour curves.

2.1.2. Sugarcane Leaf Morphology

There are two main sources of sugarcane leaves scattered in the field: some are top leaves cut from the tips of cane stalks, and the other are side leaves stripped from the fed stems. Through extensive observations, they differ in morphology, particularly in terms of leaf length. The former have a more complete sharp sword shape, with a length estimated to be between 70 and 140 cm; the latter are shorter and more belt shaped, with a length of 60 to 110 cm. More than 200 cane leaf samples were measured and statistically analyzed, and the average length measured was 78.24 cm, which was significantly larger than the values of other crops [19]. The dried leaves to be chopped were also wider, with widths concentrated at 5 to 8 cm, and also thicker, with an average thickness of 0.95 mm. The above morphological parameters comprehensively indicated that cane leaves had strong toughness, which was in line with existing research reports [20]. Therefore, the crushing energy should be strengthened in the cutting mechanism design, which is especially reflected in the density of blades and the increase in rotation speed.

2.2. Overall Structural of the Leaf-Chopping and Returning Machine

Figure 3 illustrates the overall structural configuration of the leaf-chopping and returning machine. The whole machine mainly consists of a suspension frame, a cutting roller shaft, two hook teeth assemblies for collecting leaves, specially arranged blades, a transmission system and other major components. A three-point full suspension was used to connect to the tractor, and the operating height of cutting and picking mechanisms was allowed to be adjusted by changing the hydraulic suspension position. A tractor equipped with 90 kW of power was used to ensure sufficient power output when cutting into parts of soil-covering cane leaves. Further, the overall working breadth was set to 2.0 m to have the ability to cover double rows of simultaneous crushing with one forward feed. Positioning guide rails and clamping devices were also installed to the rear of the frame for adjusting horizontal and vertical hooking positions of double teeth assemblies, so as to experimentally study the position parameters that match the furrow profile better.

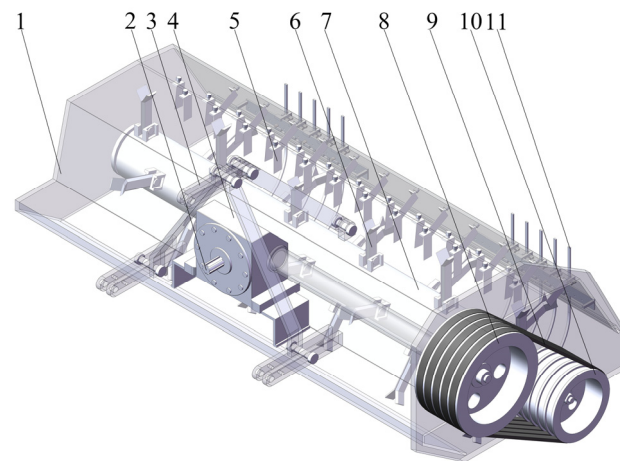


Figure 3. Structural configuration of leaf-chopping and returning machine. 1 frame, 2 power input shaft, 3 three-point suspension, 4 acceleration gearbox, 5 fixed blade, 6 L-type swing blade, 7 rotating roller, 8 driving pulley, 9 V-belt drive, 10 drive pulley, 11 flexible teeth assembly.

As far as the brief working principle of cutting mechanism is concerned, the roller shaft speed is increased by gear transmission to rotate at a high speed of about 2100 rpm. In this way, the movable blades have a large acceleration, and in cooperation with the fixed blades, leaf materials are rotated into the casing for hitting, tearing and crushing. Then, under the action of airflow and centrifugal force, leaves are evenly thrown backward along inner walls. It is worth noting that the hood is designed with a larger rotary strike space

for changing the length of the configured swing blades. The main technical parameters of the machine are summarized in Table 1.

Table 1. Main technical parameters of the whole machine.

Parameters	Details
Machine dimension (mm)	2200 × 1350 × 1100
Total mass (kg)	565
Working breadth (mm)	2000
Roller rotation speed (rpm)	1900~2100
Implement forward speed (km/h)	3~5
Supporting motive power (kW)	90

2.3. Main Components and Parameter Design

2.3.1. Profiling Arrangement of Swing Blades

The horizontally placed rotating roller and installed blades are illustrated in Figure 4. For this roller shaft with a large span, its flexural and torsional stiffness under high-frequency cutting loads are mainly ensured by increasing the wall thickness [18]. In order to handle such tough leaves, the movable swing blade is required to generate sufficient crushing cutting force [21]. For this purpose, two L-shaped 65 Mn steel blades with a thickness of 8 mm and a bending angle of 150° were used to assemble into a Y-shaped tool structure. It combined the dual-cutting action of transverse shearing and longitudinal tearing of stems and leaves, and applied multi-axial stress together with fixed blades to produce a better chopping effect [22]. In addition, the YZ6 tungsten carbide surfacing process was performed on both sides of the blade to improve wear resistance and service life.

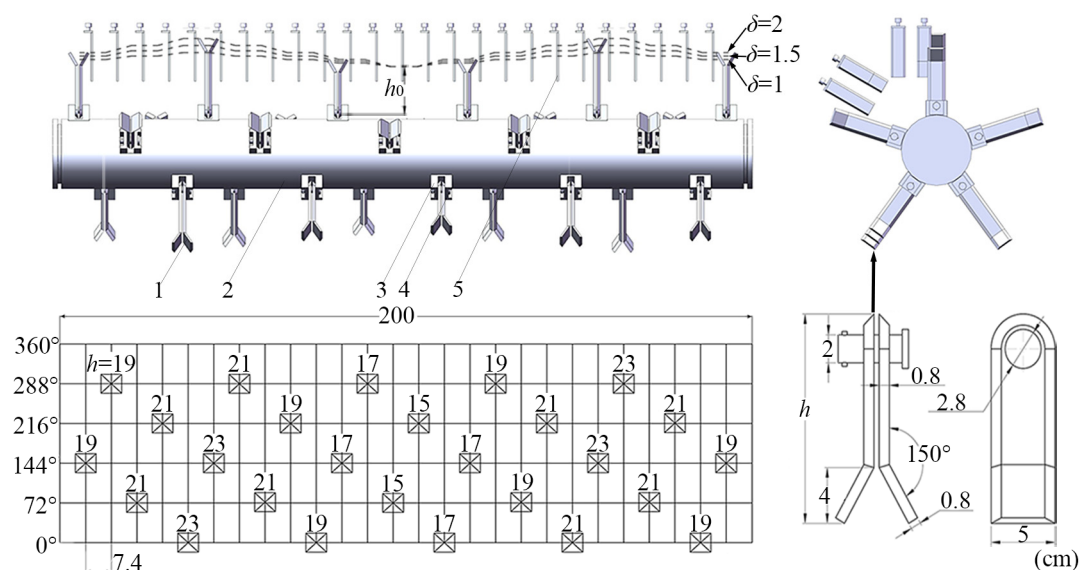


Figure 4. Profiling swing blade arrangement and specifications. 1 L-type swing blade, 2 roller shaft, 3 slotted cutter bed, 4 fixed pin, 5 fixed blade.

As shown in the expanded view in Figure 4, the swing blades are arranged in a double helix, with a total of 26 sets of Y-shaped blades to increase the axial arrangement density to increase cutting stress points. This is more conducive to improving the degree of leaf disintegration. In addition, the gap between movable and fixed blades is set smaller, which is beneficial in improving the hitting efficiency of rotary contact. Taking the upper limit of the terrain without contact with the ridge in Figure 2 as the design reference for unequal-length blades, blade groups with different lengths (h_i) arranged along the axial direction are set based on the fitted mean change trend toward the furrow sole. At the same time, a ground clearance of about 1.0 cm is maintained. Thus, the minimum blade

length (h_0) corresponding to the ridge top position is 15 cm. Furthermore, to prevent long cane leaves from being entangled [23], only one set of swing blades is arranged along each radial section of the roller. The included angle and axial distance between adjacent blade sets along the helix are 72° and 74 mm, respectively. The resulting profiled arrangement of blade edges can improve the fit to match working terrain conditions.

The design of the blade length needs to search for the optimal balance between crushing effect and cutting resistance within the terrain error area based on the criterion of not damaging stumps. Since the lengths of movable blades arranged along the same spiral are designed as per the rule of gradually increasing or decreasing with a fixed difference, the gradient of change between adjacent blade length values is defined as the growth gradient (δ), following:

$$h_{i+1} = h_i \pm \delta \quad (1)$$

As illustrated in Figure 4, $\delta = 2$ cm is used as a case. On the condition that the starting value corresponding to the vertex remains unchanged at 15 cm, δ is set to 1.0 cm, 1.5 cm and 2.0 cm. This design variable is proposed as an experimental factor for further quantitative study and optimization.

2.3.2. Flexible Hook Teeth Assembly

Facing the middle of two rows of furrows, hook teeth assemblies are installed as shown in Figure 5. Each elastic tooth is made of silicon-manganese spring steel to have enough flexible deformation to adapt to local changes in the furrow profile. The bottom of the elastic tooth is designed to be arc shaped, so that after entering the furrow, the cane leaves stacked or tightly attached to the furrow sole could be picked up, collected together, and pushed into the leaf chopper for feeding.

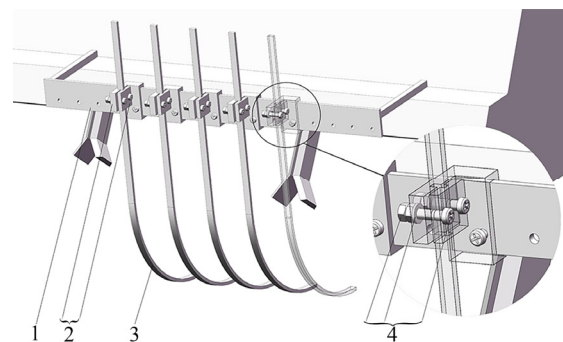


Figure 5. Structure of flexible hook teeth assembly for collecting leaves. 1 positioning guide rail, 2 clamping slide, 3 elastic teeth, 4 bolt connection.

As per the measured topography in Figure 2, the width of furrow base fluctuates more significantly than the depth. Therefore, the concentration of hook teeth arrangement is an important variable affecting their picking ability for changing furrow profiles, as also demonstrated by study [24]. In order to experiment with better profiling capabilities, by adjusting horizontal teeth spacing for a fixed number of teeth, the available range of action of hook teeth could best adapt to the morphological changes of furrows. As shown in Figure 5, the leaf collector is connected to the frame-positioning guide rail through a clamping slider, which could adjust the height above ground and the lateral action position. For avoiding excessive deformation caused by the insertion of hook teeth into the soil layer, the minimum ground clearance was set to 20 mm, and the levels set for adjustable teeth spacing were 3.5 cm, 7.0 cm and 10.5 cm.

2.4. Dynamic Analysis of Leaf-Shredding Process

In order to analyze the working mechanism of this cane leaf chopper, the interaction between cane leaves and key components was dynamically modeled, as shown in Figure 6. The shredding process of leaves could be divided into the following four stages of action:

First, the hooking of moving elastic teeth can allow the warped leaves to move upward while being pushed forward, thereby breaking away from the ground, as illustrated in Figure 6a. The picked cane leaves are more likely to be involved in the rotating cutting space, and their stress state is:

$$\begin{cases} G \sin \alpha_1 + F_a \cos \alpha_2 - f_t = ma_{x1} \\ F_t - G \cos \alpha_1 - F_a \sin \alpha_2 = ma_{y1} \end{cases} \quad (2)$$

$$f_t = \mu_t F_t \quad (3)$$

where G is the gravity of single leaf; F_a is the propulsive force of airflow on leaves; F_t is the propulsive force of elastic tooth on leaves; f_t is the friction of the elastic tooth on the leaves; m is single leaf quality; a_{x1} is the tangential acceleration of the picked leaf; a_{y1} is the normal acceleration of the picked leaf; and μ_t is the friction coefficient between the leaf and teeth.

Meanwhile, in another situation shown in Figure 6a, the cane leaves attached to the furrow sole are pushed forward and gradually accumulated under the action of hooking force. After being stacked, they are shifted to the stress state described above. The force equation of a single leaf element in this process is:

$$\begin{cases} F_t + F_a \cos \beta_2 - f_g - F_s \cos \beta_1 = ma_{x2} \\ F_G + f_t - G - F_s \cos \beta_1 - F_a \sin \beta_2 = ma_{y2} \end{cases} \quad (4)$$

$$f_g = \mu_g G + \mu_g F_s \cos \beta_1 \quad (5)$$

where F_s is the squeezing force between leaves; F_G is the ground support; f_g is the friction of the ground on the leaves; a_{x2} is the horizontal acceleration of the hooked leaves at the furrow sole; a_{y2} is another vertical acceleration; and μ_g is the friction coefficient between the leaf and the ground.

Then, as shown in Figure 6b, under the high-speed rotation of swing blades, long cane leaves within the driving range are lifted and fed at an accelerated rate. At this time, the stress state of the leaf target is:

$$\begin{cases} F_L \cos \gamma_2 + F_a \cos \gamma_3 + f_L \sin \gamma_2 - F_s \sin \gamma_1 - f_g = ma_{x3} \\ F_G + f_L \cos \gamma_2 + F_a \sin \gamma_3 - G - F_s \cos \gamma_1 - F_L \sin \gamma_2 = ma_{y3} \end{cases} \quad (6)$$

$$f_L = \mu_L F_L = \mu_L \frac{I_c \omega_L^2}{2S} \quad (7)$$

where F_L is the propulsive force of the swing blade on the leaves; f_L is the friction of the swing blade on the leaves; a_{x3} is the horizontal acceleration of the leaves; a_{y3} is another vertical acceleration; μ_L is the friction coefficient between the leaf and blade; I_c is the moment of inertia of the swing blade; ω_L is the angular speed of the roller; and S is the movement distance of the driven leaves.

Further, cane leaves rotate synchronously with a movable blade, and are successively subjected to shear impact within the matrix of blades that are mutually misaligned due to the double helix arrangement. As shown in Figure 6c, the cutting force state of cane leaf is:

$$\begin{cases} F_a \cos \delta_1 + (F_L + f_{Lc}) \sin \delta_2 - f_L \cos \delta_2 = ma_{x4} \\ (F_L + f_{Lc}) \cos \delta_2 + F_a \sin \delta_1 + f_L \sin \delta_2 - G = ma_{y4} \end{cases} \quad (8)$$

where f_{Lc} is the cutting resistance of the swing blade; a_{x4} is the horizontal acceleration of the cut cane leaf; and a_{y4} is another vertical acceleration.

Finally, when the driven leaf comes into contact with the fixed blade, a three-point support state is formed, as shown in Figure 6d. Under the action of obvious multiple shear force, cane leaves are bound to be torn. This force state can be expressed as:

$$\begin{cases} F_f + f_{fc} - f_L \sin \varepsilon_2 - (F_L + f_{Lc}) \cos \varepsilon_2 - F_a \sin \varepsilon_1 = ma_{x5} \\ f_f + F_a \cos \varepsilon_1 + (F_L + f_{Lc}) \sin \varepsilon_2 - G - f_L \cos \varepsilon_2 = ma_{y5} \end{cases} \quad (9)$$

$$f_f = \mu_t F_f \quad (10)$$

where F_f is the propulsive force of the fixed blade on the leaf; f_f is the friction of the fixed blade on the leaf; f_{fc} is the cutting resistance of the fixed blade; a_{x5} is the horizontal acceleration of the sheared leaf; and a_{y5} is another vertical acceleration.

To summarize, it can be inspired from Equations (2) and (3) that the tooth surface used for leaf collection should be machined with smaller roughness, which in turn increases the feed speed of cane leaves and prevents them from being congested in front of the hook teeth. According to Equations (4)–(7), the increase in friction with the soil will reduce the ability to propel leaves while increasing resistance load, so elastic teeth and swing blades should avoid cutting into the soil. Furthermore, increasing the roughness of the blade side edge could improve the feeding efficiency. Based on Equations (6)–(10), it is shown that appropriately increasing the rotation speed helps improve both the picking ability and the crushing force of leaves.

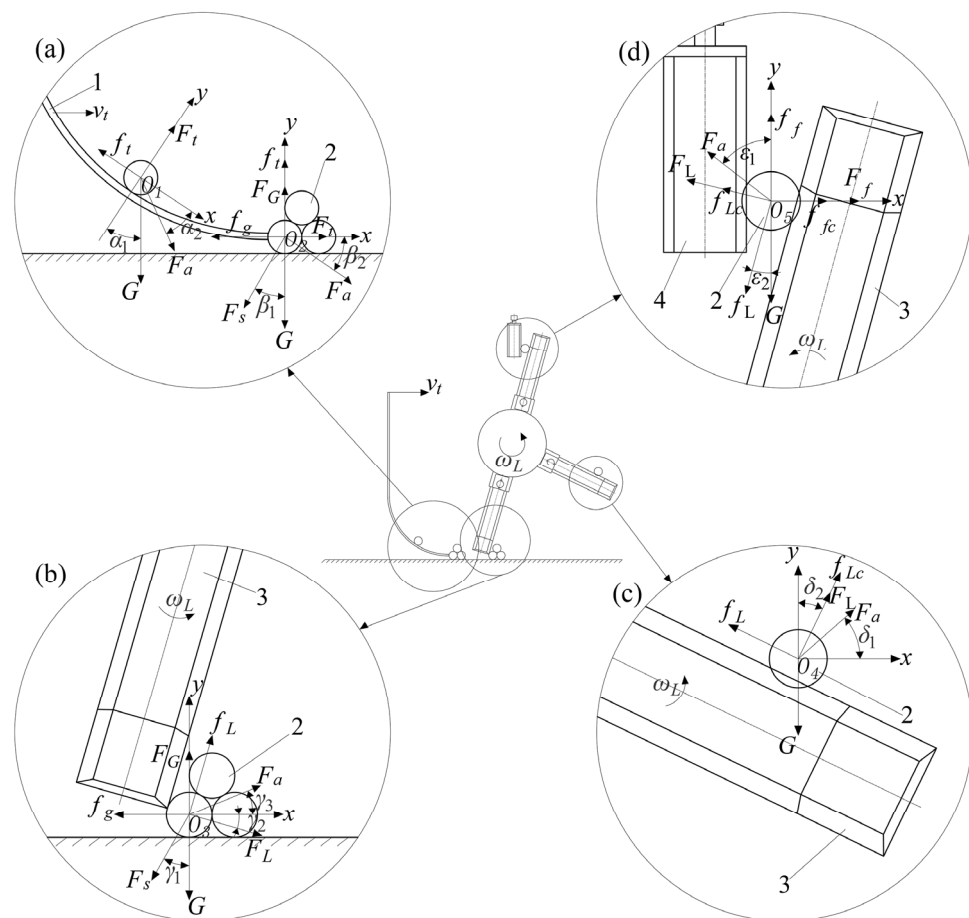


Figure 6. Dynamic analysis of leaf-shredding process. (a) Pick-up role of flexible hook teeth; (b) Lifting and feeding roles of blades; (c) Shear-cutting role; (d) Tearing role of movable and fixed blades. 1 elastic teeth, 2 cane leaves, 3 L-type swing blade, 4 fixed blade.

2.5. Field Experiment

2.5.1. Testing Conditions

The field operation site of the cane leaf-chopping and returning machine is shown in Figure 1. The individual experimental plots of the ratoon cane were selected to be 40 m × 40 m square, with a total of five plots to reflect the universal applicability of operational performance. To measure the complete distribution of leaves from furrow to ridge, a five-point sampling method was used between rows. Each quadrat was set to an area of 0.6 m from the furrow sole to the ridge top and 0.6 m along the ridge direction, as shown in Figure 7. Before each experiment, the suspension height was adjusted to keep the gap between the apex of the shortest blade tip and the ridge top at an initial value of approximately 1 cm. The suspension height was adjusted so that the gap between the apex of the blade set and the ridge top was about 1 cm.

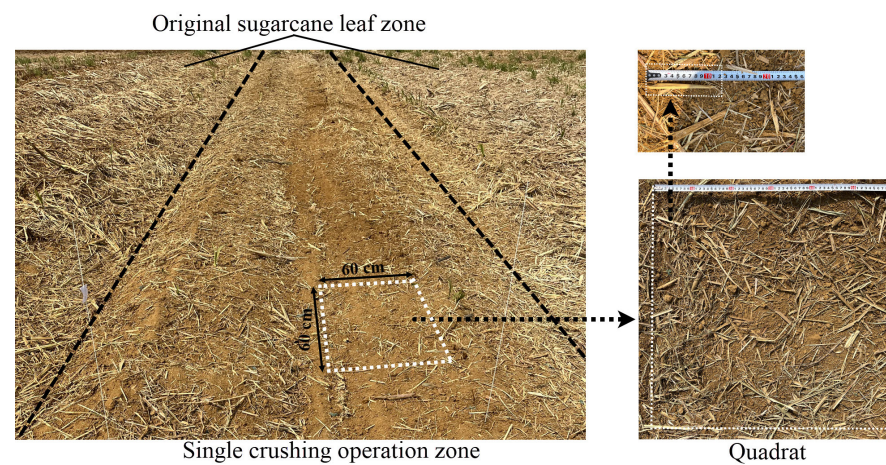


Figure 7. Quadrat for detecting cane leaves.

2.5.2. Experimental Indicators

For the effect of mechanical crushing, two indicators were set for qualitative and quantitative evaluation. First, taking the DB45/T 561-2008 standard [25] as the basic specification, the chopping qualification rate (CQR) was proposed to evaluate the quality compliance. The measurement steps are as follows: collect and weigh the mass of all cane leaves in the quadrant, noted as m_{bi} . Then, use a sieve combined with manual measurement to screen out leaves with a length standard greater than 10 cm and weigh them, recorded as m_{ai} . The average CQR of the measured values is calculated as:

$$CQR = \frac{1}{n} \sum_{i=1}^n \left(\frac{m_{bi} - m_{ai}}{m_{bi}} \right) \quad (11)$$

On the other hand, the fragmentation degree (CFD) of the crushed leaves was calculated to more accurately measure the degree of decomposition. The calculation method is as follows: randomly measure the individual length (l_i) of z pcs leaves in the quadrant; calculate the ratio of the mean value of a large number of samples to the average length before crushing ($L_0 = 78.24$ cm) to obtain:

$$CFD = \frac{1}{nL_0} \sum_{i=1}^n \frac{\sum_{i=1}^z l_i}{z} \quad (z \geq 100) \quad (12)$$

During the cane leaf-chopping process, changes in the soil depth of the tool cutting into the fluctuating field terrain will cause the resistance response of a tractor pulling implement. In this regard, a wireless strain-testing system (Type SG802, made by Beijing BeeTech Co., Ltd., Beijing, China) was used for real-time synchronous measurements. The degree of soil-engaging cutting caused by different profiling designs can be effectively characterized.

A smaller resistance value means a larger ground clearance, which corresponds to a smaller amount of crushed leaves and insufficient profiling ability; while a larger resistance value reflects an increase in the drive load due to a mismatch with the terrain, which is prone to gearbox overheating and tool wear. Thus, a detection indicator is provided for profiling arrangement design and comprehensive performance evaluation. As shown in Figure 8, the wireless signal transmitter is pasted on the upper suspension link, fixed with silicone and protected by film to reduce errors caused by high-frequency vibration and raised dust. After pre-calibration, for this system, the conversion relationship between traction resistance (F_T) and measured strain (ϵ) is followed by:

$$F_T = 0.05519\epsilon + 0.03255 \quad (13)$$

where the fitting accuracy (R^2) of this formula is 0.999 based on multiple measurement sets of tensile force and stepped strain values.

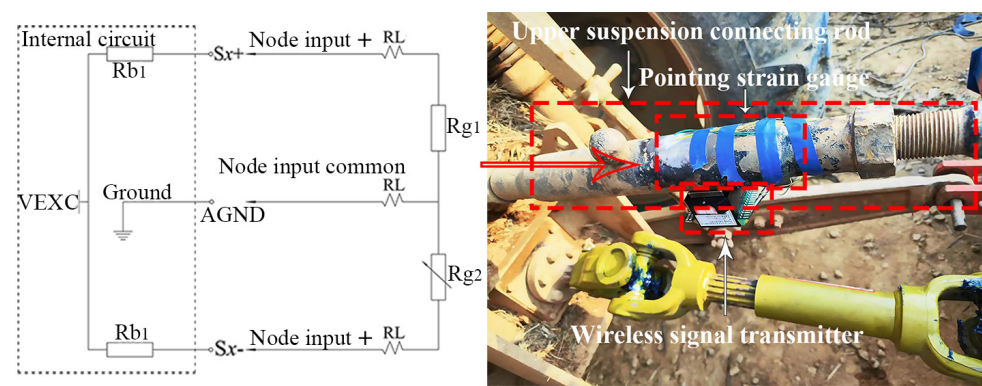


Figure 8. Wireless strain detection for traction resistance.

2.5.3. Test Scheme

In order to investigate the influence of key structural parameters and operating variables of the main components on the actual field-crushing performance, three experimental factors were extracted: blade length gradient (A), teeth spacing (B) and feed speed (C). The codes for each factor level are explained in Table 2. A total of 17 trials were conducted using the response surface test matrix of the central composite rotation design (CCD), which facilitated subsequent approximate modeling and optimization. Based on these, the influence of cutting and picking capabilities on the leaf-crushing effect can be analyzed from three aspects: the profiling degree of the blade group, the concentration of hook teeth and the processing amount of leaf materials. They were achieved by preparing three series of swing blades for replacement, adjusting horizontal and vertical installation positions of flexible teeth assemblies, and changing the forward gear of the tractor. In addition, the rotational speed of the roller was set to the maximum capacity of 2100 rpm according to the previous dynamic analysis.

Compared with the developed sugarcane leaf chopper, a conventional straw-returning machine (Type 1JHY-200, made by Hebei Gengyun Agricultural Machinery Manufacturing Co., Ltd., Handan, China) was also adopted to conduct multi-row chopping experiments on the same field to obtain a comparison of crushing performance. In addition to the above-mentioned differences in profiling and pick-up structures, the two models remain the same in terms of operating parameters such as working width, roller speed and feed speed. The CQR and CFD indicators were subsequently detected for comparison.

Table 2. Response surface test matrix and leaf-chopping performance results.

S. No	Experimental Factors			Experimental Indicators	
	Blade Length Gradient, <i>A</i> (cm)	Teeth Spacing, <i>B</i> (cm)	Feed Speed, <i>C</i> (km/h)	<i>CQR</i> (%)	<i>CFD</i>
1	1 (2.0)	−1 (3.5)	0 (4.0)	65.35 ± 3.12	0.139 ± 0.011
2	1	1 (10.5)	0	65.43 ± 2.99	0.126 ± 0.010
3	1	0 (7.0)	−1 (3.0)	75.92 ± 3.01	0.112 ± 0.010
4	1	0	1 (5.0)	75.59 ± 2.10	0.114 ± 0.004
5	−1 (1.0)	−1	0	52.44 ± 2.02	0.161 ± 0.007
6	−1	1	0	57.93 ± 1.81	0.152 ± 0.010
7	−1	0	−1	70.29 ± 2.46	0.121 ± 0.006
8	−1	0	1	59.04 ± 1.25	0.140 ± 0.010
9	0 (1.5)	−1	−1	72.27 ± 2.21	0.117 ± 0.003
10	0	1	−1	70.17 ± 2.61	0.114 ± 0.006
11	0	−1	1	60.42 ± 2.85	0.151 ± 0.009
12	0	1	1	70.02 ± 1.51	0.112 ± 0.008
13	0	0	0	82.01 ± 2.15	0.099 ± 0.009
14	0	0	0	84.82 ± 2.45	0.096 ± 0.003
15	0	0	0	82.13 ± 2.13	0.101 ± 0.006
16	0	0	0	80.25 ± 2.10	0.107 ± 0.006
17	0	0	0	80.12 ± 2.44	0.106 ± 0.003

3. Results and Discussion

3.1. Analysis of Cane Leaf-Crushing Effect

Actual measurement results of field leaf-chopping operations under changing conditions are shown in Table 2. From the analysis of variance (ANOVA) performed on different quality evaluation aspects of the crushing effect, as shown in Table 3, the regression models for both indicators are very significant. It was also found that all factors involved have a significant impact on the qualification rate. The order of influence of sources is followed by *A*, *C* and *B*, and the influence of interaction terms *AC* and *BC* is also significant on the *CQR*. From a more detailed analysis of the degree of leaf fragmentation, three single factors and the interaction term *BC* have very significant impacts on the *CFD*, and the order of their influence is *A*, *B* and *C*. The ability to conform to the field terrain, which depends on the blade and hook tooth arrangement, synergizes with the appropriate feed rate to determine the actual effectiveness of cane leaf crushing. Through the above synthesis, it is shown that the profiling design level of swing blades is the most critical.

The response surfaces of the influence of adaptive design parameters for terrain on the comprehensive crushing performance is shown in Figure 9. It is obvious that the peaks of all indicators appear at intermediate levels, indicating that the choice of the studied parameter range is reasonable. On the other hand, the slope of each surface is relatively large, which means that the optimal comprehensive crushing quality under multi-parameters and multi-objectives is within a smaller design space. Analysis of these response surfaces shows that too small or too large blade length gradients will lead to poor fragmentation due to poor overall fit with changing ridge profiles. And if hook teeth are arranged too densely or sparsely, it is not conducive to picking and collecting leaves in the furrow. Too fast feed caused insufficient unit-cutting time during the crushing process, thereby reducing both the *CQR* and *CFD*.

Table 3. Comprehensive ANOVA on field leaf-chopping performance.

Experimental Indicators	Source	Sum of Squares	DF	Mean Square	F Value	p Value	Sig
CQR	Model	1471.27	9	163.47	74.52	<0.0001	**
	A	226.74	1	226.74	103.36	<0.0001	**
	B	21.35	1	21.35	9.73	0.0168	*
	C	69.50	1	69.50	31.68	0.0008	**
	AB	7.32	1	7.32	3.34	0.1105	
	AC	29.81	1	29.81	13.59	0.0078	**
	BC	34.22	1	34.22	15.60	0.0055	**
	A ²	403.90	1	403.90	184.12	<0.0001	**
	B ²	584.71	1	584.71	266.54	<0.0001	**
	C ²	14.59	1	14.59	6.65	0.0365	*
CFD	Error	15.36	7	2.19			
	Total	1486.63	16				
	Model	61.55	9	6.84	26.20	0.0001	**
	A	8.61	1	8.61	32.99	0.0007	**
	B	5.01	1	5.01	19.20	0.0032	**
	C	3.63	1	3.63	13.91	0.0074	**
	AB	0.029	1	0.029	0.11	0.7491	
	AC	0.69	1	0.69	2.64	0.1480	
	BC	3.21	1	3.21	12.31	0.0099	**
	A ²	16.94	1	16.94	64.91	<0.0001	**
	B ²	21.16	1	21.16	81.04	<0.0001	**
	C ²	0.007	1	0.007	0.026	0.8756	
	Error	1.83	7	0.26			
	Total	63.38	16				

Note: ** means that this item is extremely significant ($p < 0.01$), * means that this item is significant ($p < 0.05$).

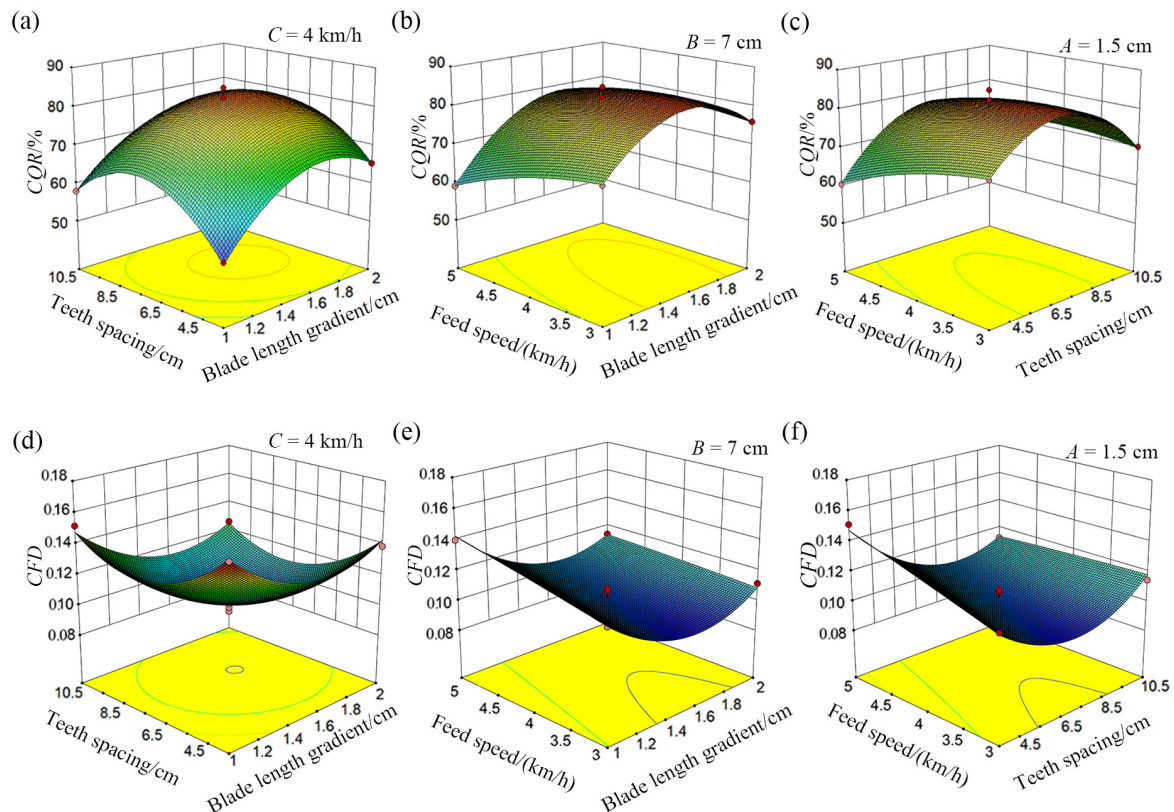


Figure 9. Response surfaces of two indicators under the influence of multi-factor interaction. (a) Influence between A and B on CQR; (b) Influence between A and C on CQR; (c) Influence between B and C on CQR; (d) Influence between A and B on CFD; (e) Influence between A and C on CFD; (f) Influence between B and C on CFD.

3.2. Approximate Modeling and Optimization Validation

Based on the response surface results, non-significant items were eliminated according to their p values, and mathematical approximate relationships were established for the two crushing indicators:

$$\begin{cases} CQR = 81.87 + 5.32A + 1.63B - 2.95C + 2.73AC + 2.92BC - 9.79A^2 - 11.78B^2 - 1.86C^2 \\ CFD = 10.19 - 1.04A - 0.79B + 0.67C - 0.90BC + 2.01A^2 + 2.24B^2 \end{cases} \quad (14)$$

where the goodness of fit (i.e., regression coefficient, R^2) of these developed approximate models was greater than 0.9, which was enough to cover the entire design space. In order to optimize the overall leaf-chopping quality and obtain an optimal parameter combination that coordinates multi-faceted capabilities of profiling, picking and feeding, the mathematical expression of this multi-objective optimization problem is set as:

$$\begin{cases} \max CQR(A, B, C) \\ \min CFD(A, B, C) \\ \text{s.t.} \begin{cases} 1 \leq A \leq 2 \\ 3.5 \leq B \leq 10.5 \\ 3 \leq C \leq 5 \end{cases} \end{cases} \quad (15)$$

The optimal design solution set obtained by using a genetic optimization algorithm is: blade length gradient of 1.57 cm, teeth spacing of 6.84 cm, and feed speed of 3.2 km/h. In this state, the predicted CQR reached a larger value of 83.16%, and at the same time the CFD reached a more thorough fragmentation of 0.094. Accordingly, by reprocessing blade groups, adjusting teeth assembly installation and feed speed conditions, field verification tests were carried out using optimal parameter settings. The results show that the measured CQR and CFD reached 81.14% and 0.101, respectively. Such a prediction error of less than 3% indicates that the optimized performance has achieved the desired operating effect.

3.3. Comparison on Improvements in Crushing Quality

The detection results of corresponding crushed leaves showed that the average CQR and CFD were 20.64% and 0.194, respectively. Comparison of these results of the original model with the new model shows that the chopper modified for use in furrow-ridge terrain has improved CQR by 60.50% and CFD by 47.99%.

On the other hand, as illustrated in Figure 10, analysis from the perspective of field ridge appearance and leaf distribution after operation demonstrates that, for the straw-returning machine, there are still a large amount of unqualified long cane leaves that have not met the crushing standard accumulated in the treated furrow area. Moreover, the tool cut off part of the ridge surface, causing serious damage to the ridge body with buried perennial roots. However, in contrast, after the operation of the profiling leaf crusher, there exists no obvious long leaf remaining in the furrow, and the treated leaves are more fully mixed with the soil and distributed more evenly, which is beneficial to improving the efficiency of converting leaf organic matter into soil fertility [26]. To sum up, the comprehensive improvement effect of profiling modification on leaf-chopping performance is very significant.

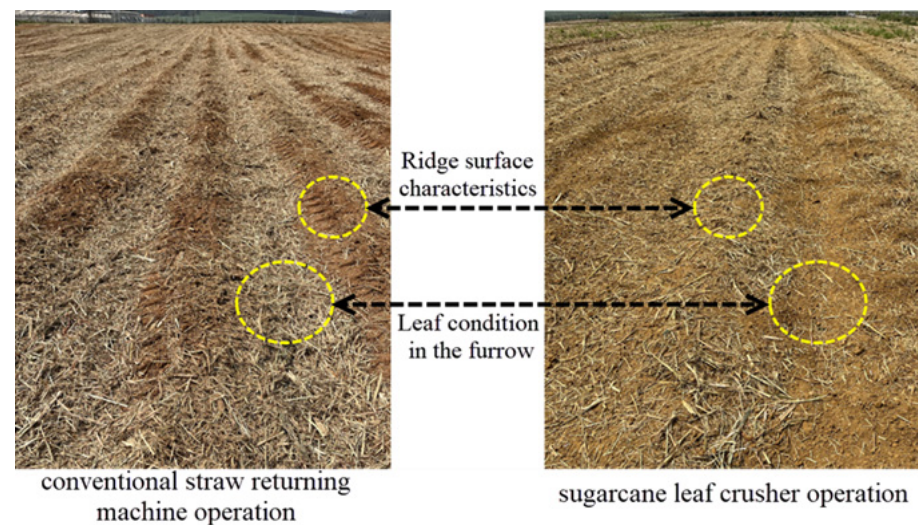


Figure 10. Comparison of ridge appearance and leaf distribution before and after machine modification.

3.4. Analysis of Resistance Characteristics

The traction load of the leaf-chopping machine has the ability to reflect the overall soil-engaging level of the rotary cutting of the swing blades, that is, the profiling capability of field terrain. Figure 11 shows the traction resistance characteristics under the optimized blade arrangement of 1.57 cm length gradient during operation, and its response comparison with other larger and smaller blade gradients, while other parameters remain unchanged. The variation in the curve illustrated that the machine reached the normal working state about 10 s after it was started. As shown in Figure 11a,b, the resistance values generated by the machine designed with a gradient lower than 1.57 cm tended to be stable, basically fluctuating in the range of ~0.2–0.5 kN, which was mainly caused by tractor vibration and unbalanced transient cutting forces [27]. Their effective values (i.e., root mean square, RMS) were calculated to be 0.346 kN and 0.347 kN, respectively. These two similar results demonstrated that an overall increase in blade length below the optimal gradient did not result in more pronounced ridge cutting. It further proved that the degree of fit after optimization was appropriate or may be improved.

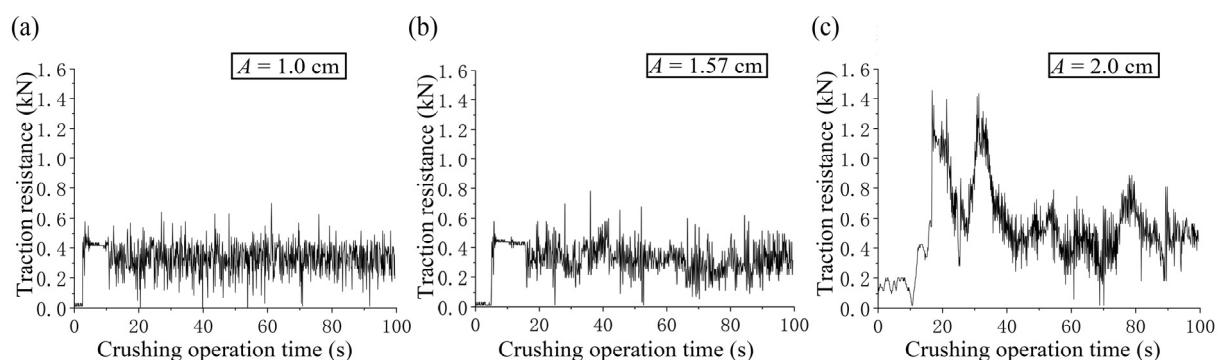


Figure 11. Comparison of traction resistance using blade arrangements with different length gradients. (a) Smaller level of 1.0 cm; (b) Optimized gradient of 1.57 cm; (c) Larger level of 2.0 cm.

In contrast, as shown in Figure 11c, as the blade gradient was increased by one level to 2.0 cm, the fluctuation amplitude of the traction resistance obtained was significantly larger, reaching 1.45 kN, 1.42 kN and 0.89 kN at 15 s, 35 s and 78 s, respectively. This means that due to the longer blade design and real-time elevation of the current terrain, the depth of the in-soil cut increased, reflecting the ridge-cutting phenomenon, generally becoming more severe. Its RMS value was calculated to be 0.639 kN, which was 45.85% higher than the optimized RMS, thus verifying that the tool arrangement designed with a

1.57 cm gradient had a better overall match with the changing furrow-ridge terrain. This provided direct experimental evidence for improving the effect of cane leaf chopper and achieving better energy consumption performance.

4. Conclusions

1. This paper designs a profiling configuration of chopping and returning machine that adapts to the coverage characteristics of sugarcane leaves in furrow-ridge terrain. The device is powered by a tractor, and collects leaves attached to the furrow through a flexible hook teeth assembly. The rotating dense swing blades of unequal lengths cooperate with fixed blades to constitute a hitting space to chop the fed leaf materials. The profiling arrangement adopted effectively solves the problem of incompatibility with ridge cultivation terrain;
2. The profiling parameters for terrain fit were determined based on the measured terrain change trends and combined with a dynamic analysis of the leaf-shredding process. Structural and operating factors that affect the cutting and picking capabilities were determined, such as blade length gradient, teeth spacing and feed speed. On this basis, *CQR* and *CFD* were selected as test indicators, and field experiments with three factors and three levels were conducted using the response surface method;
3. The influence of various factors on *CQR* and *CFD* was significant, and mathematical regression models were established accordingly, which illustrated the rationality of studied parameter ranges. From ANOVA, the profiling design level of swing blades is the most critical among factors. The multi-objective optimal operation parameter combination of such a cane leaf-chopping and returning machine was obtained as: blade length gradient of 1.57 cm, teeth spacing of 6.84 cm and feed speed of 3.2 km/h. Utilizing this adaptive configuration, *CQR* and *CFD* were significantly improved by 60.50% and 47.99%, respectively, compared to the conventional machines. Meanwhile, crushed leaves were more thoroughly mixed with the soil and spread more evenly in the field;
4. The effective value *RSM* of traction resistance under the optimized tool arrangement was 45.85% lower than that of the higher-level blade length. The stable operating characteristics demonstrated that it fitted well with the changing furrow-ridge terrain. The comprehensive crushing quality and resistance results can meet the agronomic practice requirements for the promotion and application of sugarcane leaf returning in ridge cultivation fields.

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