EXPERIMENTAL STUDY ON THE PERFORMANCE OF CORN STALK CRUSHING DEVICE WITH STEPPED SAW DISK KNIFE
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阶梯式锯盘刀玉米秸秆粉碎装置性能试验研究

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ABSTRACT
Responding to the problem of over-returning of corn stalk to the field, this article proposes a comprehensive utilization model that returns 30% of corn stalk to the field from above the surface and recycles the remaining 70% as fodder is proposed. For the problems of poor quality of stalk crushing and fast knife wear, the experimental platform for corn stalk crushing with vertical shaft stepped saw disc knife was designed. The effects of different factors on the qualified rate of stalk cutting length and cutting power were investigated. The qualified rate of cutting length was the best 96.57% when the plant spacing was 20 cm. The cutting power was the smallest 322.94 W when the rotational speed of knife roller was 600 r/min. The stalk crushing process was analysed by high-speed camera, and the stalk crushing mechanism was clarified.

摘要
针对玉米秸秆还田量过大的问题，本文提出了将玉米秸秆自地表以上30%还田，其余70%回收作饲料的综合利用模式。针对秸秆粉碎质量差、刀片磨损快等问题，设计了立轴阶梯式锯盘刀玉米秸秆粉碎试验台，实现秸秆离地粉碎。通过单因素试验，探究了刀辊转速、喂入速度、钳住角、拨禾星轮转速、株距对秸秆切断长度合格率和切割功率的影响规律。当株距为20 cm，切断长度合格率达到最高为96.57%。当刀辊转速为600 r/min 时，切割功率达到最小为322.94 W。通过高速摄像对秸秆粉碎过程进行了分析，明晰了秸秆粉碎机理。

INTRODUCTION
Stalk crushing and returning to the field has many advantages, which is the main way of stalk utilization at present *(Ramm et al., 2024; Li et al., 2024; Miranda et al., 2021; Liu et al., 2019; Yeboah et al., 2017)*. However, the amount of stalk returned to the field is too large and cannot be effectively decomposed and utilized. In addition, the traditional devices for returning corn stalk to the field are mainly the hammer claw type and the dumping knife type. It is near-ground operation, and the knife inevitably contact with soil, stones and so on, resulting in rapid wear and bluntness of the knife blunt. Therefore, it cannot cut of the stalk fibre effectively, and the operation power consumption is large *(Zhang et al., 2019; Yu et al., 2019)*.

To improve the cutting effect and reduce the cutting power, scholars have studied the cutting theory, mechanism design and parameter optimization of corn stalk returning devices. *Gupta et al., (1996),* studied the effect of operating parameters of single disc cutter on the cutting performance of sugarcane. *Mello et al., (2000),* compared the differences between angled and serrated blades in reducing cutting loss and cutting force through experiment, and analysed them by high-speed cameras. *Igathinathane et al., (2010),* tested the effect of cutting angle on cutting force and cutting power of corn stalk. *Geng et al., (2021),* designed a corn stalk kneading and conveying device to achieve stalk conveying while cutting stalk. *Zhao et al., (2022),* designed a cutting knife for corn stalk by bionic the mandibular teeth of ants. *Sun et al., (2019),* designed a differential speed stalk returning machine with circular saw knives and crushing knives working in the same direction. *Wang et al., (2020),* designed a chopping device to improve the decomposition rate of stalk returning to the field. *Zhao et al., (2021),* designed a bionic stalk returning knife based on primnoa mouthparts to reduce the cutting power. *Liu et al., (2021),* designed a dynamic supported corn stalk chopping device with different rotational speed of disc knife.

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Song et al., (2024), experimented the parameters of stalk returning machine and obtained the optimal parameter combination. However, there are fewer studies on the appropriate amount of stalk returned to the field and the related mechanical devices based on it.

Aiming at the problems of poor quality of stalk crushing and fast knife wear, an experimental platform for corn stalk crushing with stepped saw disc knife composed of multiple circular saw knives of different diameters was designed to achieve off-ground crushing of stalk. The factors affecting the qualified rate of cutting length and cutting power of corn stalk were experimented through the experimental platform, and the stalk crushing process was analysed by high-speed camera. The research provides theoretical basis and design basis for the design of stalk crushing device of corn harvester.

MATERIALS AND METHODS

The crushing experimental platform with stepped saw disc knife

The comprehensive utilization mode of corn stalk

If the entire corn stalk is returned to the field, the amount of returned stalk is too large, which not only affects the subsequent sowing and emergence of wheat, but also the stalk cannot be effectively decomposed and utilized *(Li et al., 2022; Zhu, 2019; Qiao, 2019)*. Recycling all of them cannot fully utilize the effect of stalk returning to the field on improving soil organic matter and promoting wheat yield. So, a comprehensive utilization model that returns 30% of corn stalk to the field from above the surface and recycles the remaining 70% as fodder is proposed *(Dong et al., 2010; Wang et al., 2013)*, as shown in Fig. 1.

Fig. 1 - The comprehensive utilization mode of corn stalk

The machine structure and operating principle of the experimental platform

It is difficult to accurately adjust the operating parameters and inconvenient to collect data when the field experiment is conducted directly by the corn stalk returning machine. Therefore, based on the principle of comprehensive utilization of corn stalk, an experimental platform of stepped saw disc is designed, which mainly consists of three parts: stepped saw disc crushing device, clamping feeding device, control and data acquisition system, as shown in Fig. 2. The clamping feeding, crushing, and data collection of corn stalks are completed at one time.

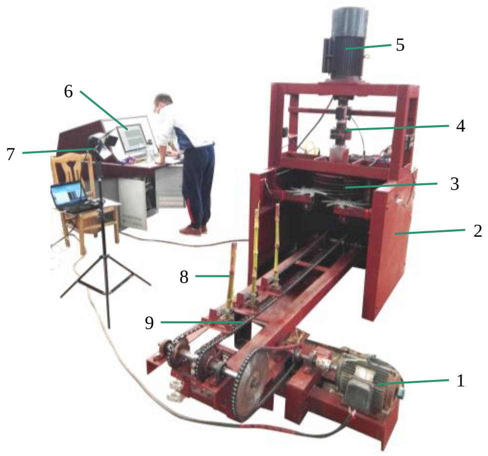


Fig. 2 - The crushing experimental platform with stepped saw disc knife

1 - Motor of clamping feeding device; 2 - Crushing device of stepped saw disc knife; 3 - Stepped saw disc knife; 4 - Torque sensor; 5 - Motor of the crushing device; 6 - Devices of control and data collection; 7 - High-speed camera; 8 - Corn stalk; 9 - Clamping feeding device

The core component of the stepped saw disc knife consists of multiple circular saw knifes of different diameters, as shown in Fig. 3. The saw disc knifes are arranged in a stepped manner, and their diameter gradually decreases from top to bottom. There is a relative velocity between neighbouring saw disc knifes. Not only cutting the stalk, but also tearing it, which is more conducive to the crushing and subsequent decay of the stalk. In addition, the corn stalks are crushed in an upright state, the saw disc knife does not touch the soil, so the saw teeth can remain sharp for a long time to ensure better crushing effect *(Zhang et al., 2021)*.

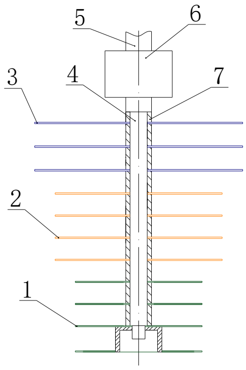


Fig. 3 - The stepped saw disc knife

1 - Circular saw knife with a diameter of 200 mm; 2 - Circular saw knife with a diameter of 280 mm;
3 - Circular saw knife with a diameter of 360 mm; 4 - Shaft of the knife; 5 - Shaft of the motor; 6 - Coupling; 7 - Bushing

Sawing and crushing experiment of corn stalk

Experimental materials

The corn variety used for the experiment is Zhengdan 958, and the average value of stalk diameter is 20.78 mm, and the average value of moisture content is 78.30%. Corn stalks with equivalent outer diameter and without epidermal damage are selected for the experiment.

Experimental indexes

Referring to the relevant standards *(GB/T 5262 - 2008; NY/T 500 - 2015)*, the experiment is conducted with the qualified rate of stalk cutting length and cutting power as the experiment indexes.

The qualified rate of cutting length F_n:

$$F_n = \frac{m_z - m_b}{m_z} \times 100\% \tag{1}$$

m_b - the mass of stalk with unqualified lengths [kg]; m_z - the total mass of stalk [kg].

The cutting power P_q:

$$P_q = \frac{n(T_z - T_k)}{9550} \tag{2}$$

T_k - the torque during idling [N·m]; T_z - the total torque during operation [N·m].

Single-factor experiment

The rotational speed of the knife roller, stalk feeding speed (i.e. machine forward speed), clamping angle, rotational speed of the dial wheel and stalk plant spacing are taken as the experimental factors, and the experiment is repeated five times to take the average value. The level coding table of experimental factor is shown in Table 1. The rotational speed of the knife roller of 800 r/min, feeding speed of 1.45 m/s, rotational speed of the dial wheel of 110 r/min, clamping angle of 15° and plant spacing of 30 cm are taken as the zero level.

Table 1

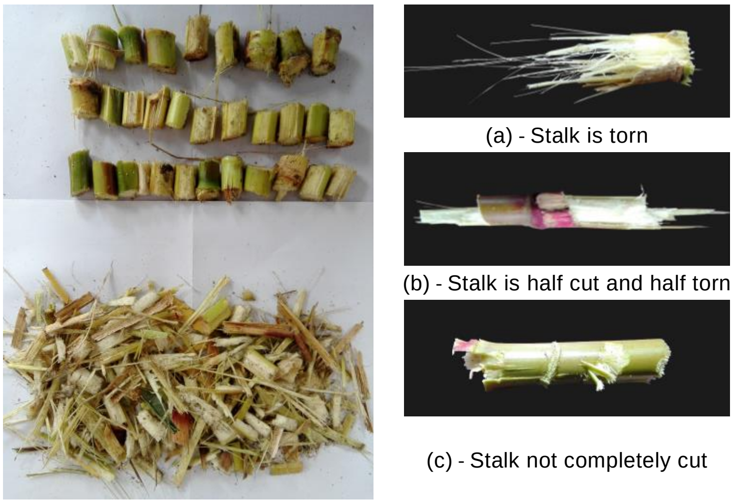
Level coding table of experimental factors

Level	**Factors**				
	Rotational speed of the knife roller [r/min]	**Feeding speed of the stalk [m/s]**	**Clamping angle [°]**	**Rotational speed of the dial wheel [r/min]**	**Plant spacing of the stalk [cm]**
1	600	0.75	-15	50	20
2	700	1.10	0	80	25
3	800	1.45	15	110	30
4	900	1.80	30	140	35

RESULTS

Rotational speed of the knife roller

The stalk that has been cut and crushed is shown in Fig. 4, in which most of them are cut into small sections of 30 mm, the length of which meets the requirements, and the stalk fibre can be effectively cut. The length meets the requirements, and the stalk fibres can be effectively cut. The tearing of stalk by the teeth of the saw disc knife is shown in Fig. 4(a). However, the length of individual stalks after cutting is unqualified, as shown in Fig. 4(b), the stalks are half cut and half torn. There are also stalks that are not completely cut, as shown in Fig. 4(c).



(a) - Stalk is torn

(b) - Stalk is half cut and half torn

(c) - Stalk not completely cut

Fig. 4 - Crushed stalk

The effects of the rotational speed of the knife roller on the qualification rate of cutting length and cutting power are shown in Fig. 5. The qualified rate of cutting length of corn stalk shows a trend of increasing and then decreasing with the increase of the knife roller rotational speed, and the qualified rate of cutting length is non-linearly correlated with the rotational speed of the knife roller. When the rotational speed of the knife roller is 800 r/min, the qualified rate of cutting length reaches best 85.59%. The reason is that, with the increase of rotational speed of the knife roller, the impact of knife roller on corn stalk increases, and the stalk is difficult to feed into the knife roller, which leads to the decrease of qualified rate of cutting length. The cutting power increases with the increase of rotational speed of the knife roll. The cutting power is the smallest 322.94 W when the rotational speed of the knife roll is 600 r/min. The growth rate of cutting power is basically the same, and they are linearly correlated. The rotational speed of the knife roller is the main factor affecting the cutting power.

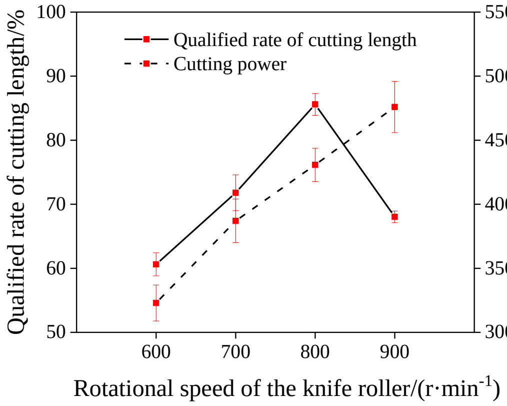


Fig. 5 - Effect of the rotational speed of the knife roller on the experimental indexes

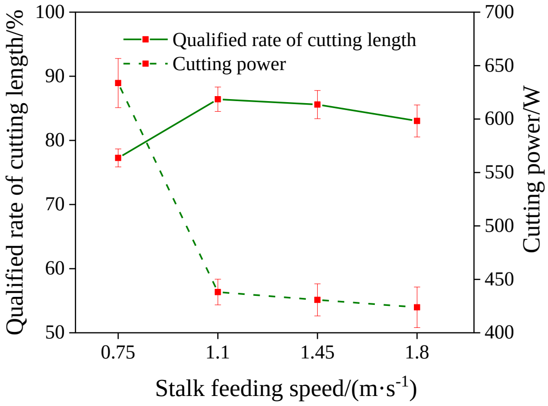


Fig. 6 - Effect of the feeding speed on the experimental indexes

Stalk feeding speed

The effects of stalk feeding speed on the qualification rate of cutting length and cutting power are shown in Fig. 6. The qualified rate of cutting length shows a trend of increasing and then decreasing with the increase of stalk feeding speed.

When the feeding speed is 1.10 m/s, the qualified rate of cutting length reaches the best level 86.42%. The reason is that, with the increases of feeding speed, the number of corn stalks cut by the knife rollers per unit time increases, and the effective cutting time of a single corn stalk decreases, resulting in inadequate cutting of the stalks. Secondly, with the increase of feeding speed, the collision and impact between corn stalks and knife rollers increase, and the stalks cannot be fed efficiently, resulting in a decrease in the qualified rate of cutting length.

The cutting power decreases with the increase of feeding speed, and they are negatively correlated. The cutting power reaches a minimum of 423.81 W when the feeding speed is 1.80 m/s. The reason is that with the increase of feeding speed, the effective cutting time of single corn stalk is reduced, and the stalk is not sufficiently cut, and even missing cutting due to stalk cannot be fed. When the feeding speed increases from 0.75 m/s to 1.10 m/s, the cutting power is reduced by 30.88%, which is a significant reduction. The reduction is significantly reduced when the feeding speed exceeds 1.10 m/s. It shows that as the feeding speed continues to increase, its effect on cutting power becomes less and less.

Clamping angle

The effects of clamping angle on the qualification rate of cutting length and cutting power are shown in Fig. 7. The qualified rate of cutting length shows a trend of first increase and then decrease with the increase of clamping angle. When the clamping angle is 15°, the qualified rate of cutting length reaches the best 88.58%. When the clamping angle is -15°, the qualified rate of cutting length is the lowest 65.40%. The reason is that at this time, the rotation direction of the dial wheel is opposite to the direction of stalk feeding, which is not conducive to the feeding of stalk. This indicates that when corn stalk is fed into the knife rollers from an area with negative clamping angle, the cutting effect is not ideal. The cutting power increase and then decrease with the increase of clamping angle. When the clamping angle is 15°, the cutting power reaches a maximum of 440.75 W. When the clamping angle is -15°, the cutting power reaches a minimum of 372.11 W.

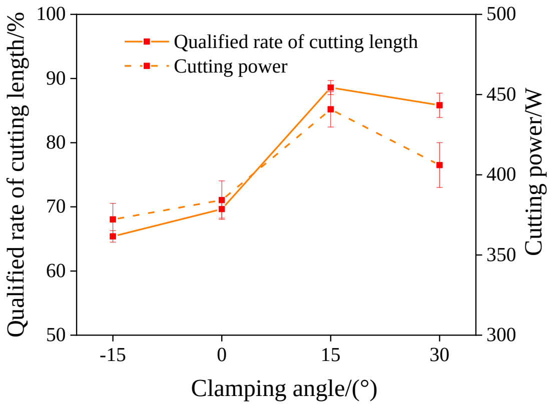


Fig. 7 - Effect of the clamping angle on the experimental indexes

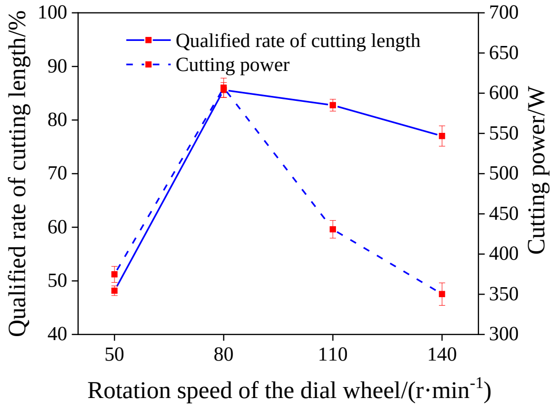


Fig. 8 - Effect of the rotational speed of the dial wheel on the experimental indexes

Rotational speed of the dial wheel

The effects of the rotational speed of the dial wheel on the qualification rate of cutting length and cutting power are shown in Fig. 8. The qualified rate of cutting length increase and then decrease with the increase of the rotational speed of the dial wheel. When the rotational speed of the dial wheel is 80 r/min, the qualified rate of cutting length reaches the best level 85.59%. The reason is that, with the increase of the rotational speed of the dial wheel, the speed of the stalk in the instant of cutting suddenly increases, the impact between the stalk and the knife roller increases, which reduces the qualified rate of cutting length. The cutting power increases and then decreases with the increase of the rotational speed of the dial wheel. The cutting power is the smallest 350.16 W when the rotational speed of the dial wheel is 140 r/min. At this time, the rotational speed of the dial wheel is too fast and cannot match with the knife roller speed and stalk feeding speed, and the stalk is not sufficiently cut or missed, which leads to a smaller cutting power.

Plant spacing of the stalk

The effects of plant spacing on the qualification rate of cutting length and cutting power are shown in Fig. 9. The qualified rate of cutting length decreases with the increase of plant spacing, and they are negatively correlated. When the plant spacing is 20 cm, the qualified rate of cutting length is the best 96.57%. With the increases plant spacing, the qualified rate of cutting length gradually decreases, but the decrease of each section does not exceed 10%.

It indicates that its effect on the qualified rate of cutting length becomes smaller and smaller with the increases of plant spacing. The cutting power decreases with the increase of plant spacing and the decrease of cutting power is essentially the same. When the plant spacing is 35 cm, the cutting power is the smallest 358.33 W. With the increase of plant spacing, the feeding gap between neighbouring corn stalks increases, and the probability of stalk congestion decreases, so the cutting power gradually decreases.

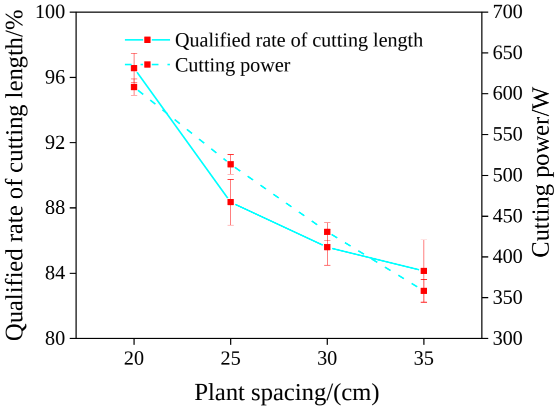
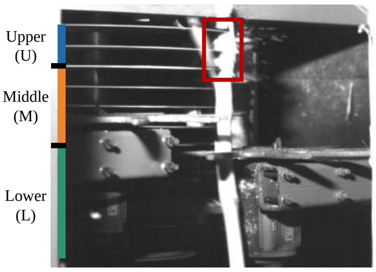


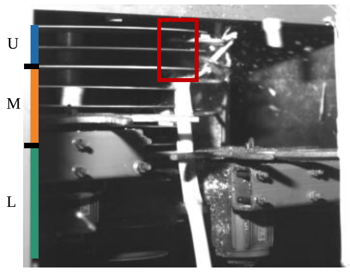
Fig. 9 - Effect of the stalk plant spacing on the experimental indexes

The analysis of high-speed camera

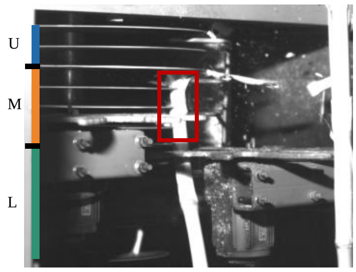
The process of crushing corn stalks with the stepped saw disc knife is analysed by high-speed camera, and the results are shown in Fig. 10. Corn stalk fixed on the clamping feeding device is transported to the knife rollers. Since the diameter of the saw disc knife in the upper region of the knife roll is the largest, the upper part of the stalk is cut first, as shown in Fig. 10 (a) and (b). The saw teeth squeeze the stalk for sliding cut, cutting the stalk while tearing and crushing it. After the upper part of the stalk is crushed, the middle part of the stalk starts to be cut and crushed by the saw disc knives in the middle area of the knife rollers, as shown in Fig. 10 (c) and (d). To the lower part of the stalk, as shown in Fig. 10 (e) and (f), at this point, a corn stalk is completely crushed. Through the high-speed camera analysis of the stalk crushing process, the corn stalks are cut sequentially from top to bottom, which meets the design requirements of the stepped saw disc knife.



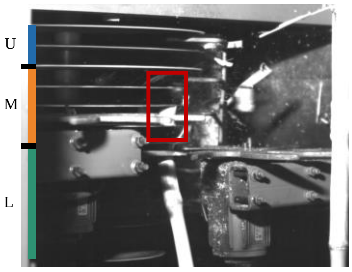
(a) - The upper part begins to be cut



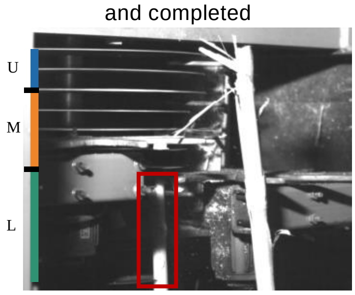
(b) - The upper part has been crushed and completed



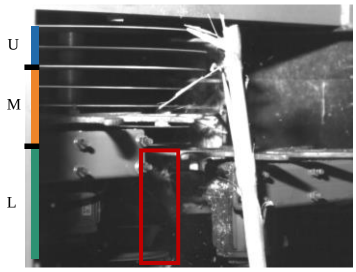
(c) - The middle part begins to be cut



(d) - The middle part has been crushed and completed



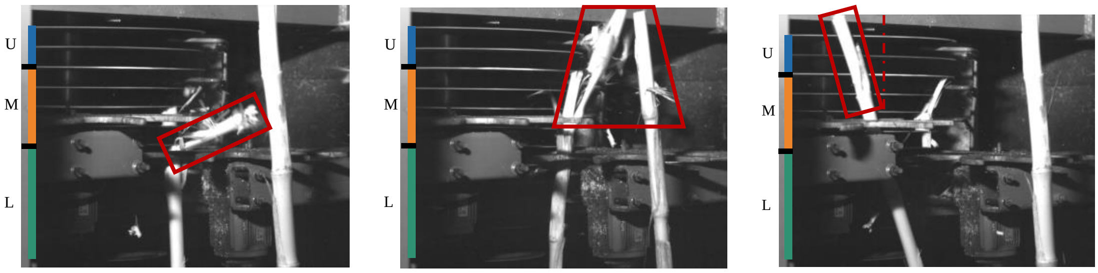
(e) - The lower part begins to be cut



(f) - The lower part has been crushed and completed

Fig. 10 - The crushing process of corn stalk

The failure of stalk during crushing is analysed by high-speed camera, and the failure of stalk is shown in Fig. 11. Fig. 11(a) shows that the stalk is broken due to collision and impact by the knife rollers. Fig. 11(b) shows that the stalk is congested in the cutting process because the feeding speed of the stalk is too fast. In Fig. 11(c), the stalk is difficult to be cut without being clamped by the saw disc knife when the clamping angle is negative.



(a) - Stalk is broken by impact (b) - Stalk congestion (c) - Negative clamp angle

Fig. 11 - The cutting failure of corn stalk

CONCLUSIONS

(1) A comprehensive utilization model that returns 30% of corn stalk to the field from above the surface and recycles the remaining 70% as fodder was proposed. Based on this, the experimental platform for corn stalk crushing with stepped saw disc knife was designed to achieve off-ground crushing of stalk.

(2) The results of the single-factor experiment showed that the qualified rate of cutting length increased and then decreased with the increase of knife roller rotational speed, feeding speed, clamping angle and dial wheel rotational speed, and decreased with the increase of plant spacing. When the plant spacing was 20 cm, the qualified rate of cutting length is the best namely 96.57%.

(3) The results of the single-factor experiment showed that the cutting power increased with the increase of knife roller rotational speed, decreased with the increase of feeding speed and plant spacing, and increased and then decreased with the increase of clamping angle and the dial wheel rotational speed. When the rotational speed of the knife roll was 600 r/min, the cutting power was the smallest 322.94 W.

(4) The high-speed camera analysis of the corn stalk crushing process showed that the stepped saw disc knife could completely cut off the stalk fibres and improved the quality of corn stalk crushing.

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