Design of variable screw pitch rib snapping roller and residue cutter for corn harvesters

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Abstract: The blocking between two snapping rollers will seriously constrict the harvesting efficiency for corn harvester. A variable screw pitch rib snapping roller was developed to solve this problem. The comparative experiment between fixed screw pitch rib snapping rollers and variable screw pitch rib snapping rollers illustrated that variable screw pitch ribs can avoid corn-stalk blocking effectively, and it can improve working efficiency by 56.7%. Conservation tillage with standing corn residue was testified that it had a strong control of soil wind erosion. In order to implement this mode of conservation tillage at a production scale, a cutter was developed in this study. Subsequently, two experiments were conducted, one was to test the cutting ratio (defined as the totally cut off stalk population divided by total stalk population), and the other one was to test standing-residue height. The experiment results showed that the mean cutting ratio increased significantly ($p<0.05$) along with increasing height of cutter-head above the ground (cutting height); the cutting ratio's mean value increased significantly ($p<0.05$) along with the decreasing angle between the cutter-head and the ground (cutting angle). The average standing-residue height increased along with the increase of cutting height from 300 mm to 500 mm. The average standing-residue height increased significantly ($p<0.05$) along with the decrease of cutting angle from 15° to 0°. Therefore, the newly designed snapping roller can improve the harvesting efficiency and prolong the working life of the cutting table; and the cutter can promote the popularization of the conservation tillage with standing corn residue in Northeast China.

Keywords: corn harvester, variable pitch, snapping roller, standing corn residue, field imitating experiment, cutting height, cutting angle
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1 Introduction

Many horizontal-roller corn harvesters are using in Northeast China now, one of main serious concerns of these horizontal-roller corn harvesters was the blocking between two snapping rollers[1]. The horizontal snapping roller has three portions: tapering portion, body portion and cut portion. Since corn stalks enter the gap of two snapping rollers, corn stalks move towards backward and downward relative to snapping rollers, if the corn stalk was still in the gap until it reached the end

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of cut portion, blockings would occur[2]. This blocking will be more serious when the harvester operated at a high speed, therefore it is a main limitation to improve the harvester's working efficiency.

In Northeast China, one kind of conservation tillage with standing corn residue is emerging now, compared with traditional conservation tillage through shattering the stalks into small sections and spreading them on soil surface; standing corn residue can control soil wind erosion effectively[3]. Fryrear and Bilbro[4] obtained a conclusion that standing stalks are at least five times more effective for controlling wind erosion than flat residues. After the upper part of the stalk of standing corn residue is cut and the bottom part of the standing corn stalk is left, therefore, the bottom part will still be standing in the field[5,6]. One observed advantage of the standing residue technique relates to the collection of upper part stalks, since corn stalks are major winter livestock forage in most rural areas all over the world[7]. Using 100% crop biomass to cover fields reduces available stalk amount for feed markets[8].

In this study, the new snapping roller was designed and tested in order to solve the blockings problem. The snapping roller could reduce the backward speed of corn stalk, but the downward speed of corn stalk would be constant, so all the corn stalks could be pulled out of the gap before they reach the end of cut portion. A rotary knife cutter was designed in this study, too. The cutter-head rotates at high speed and cuts the stalks with free support. In addition, the cutting height and cutting angle could be adjusted according to the agricultural requirements, thus the cutter can help corn harvesters to realize conservation tillage with standing corn residue.

2 Materials and methods

2.1 Snapping rollers with variable screw pitch ribs

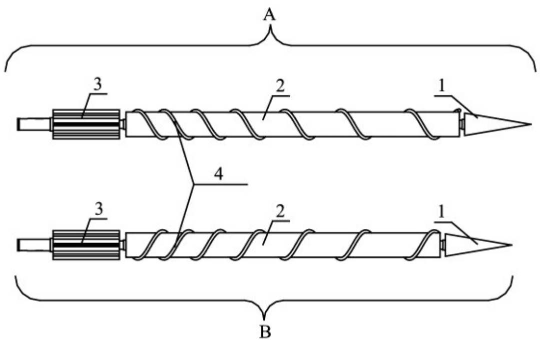
As shown in Figure 1, the screw ribs on the snapping roller was designed with variable screw pitch from the front to the back, which is different from the common snapping rollers. And if we put the body portion of this snapping roller in the coordinate system, and the axis of body portion was overlapped with the 'z' axis, and the front-transect was overlapped with 'x-y' plane, the screw ribs could be presented as the following equations.

$$\begin{cases} x = 44\cos\theta \\ y = 44\sin\theta \\ z = -7.7\times 10^{-5}\theta^2 + 0.542\theta \end{cases} \quad (1)$$

$$\begin{cases} x = 44\cos\theta \\ y = 44\sin\theta \\ z = -7.7\times 10^{-5}\theta^2 - 0.542\theta \end{cases} \quad (2)$$

where, Equation (1) represents the equation of inner snapping roller, Equation (2) represents the equation of outer snapping roller, θ is the rotation angle, (°).

The aim of this design was to solve the problem of corn stalk blocking in the gap between two snapping rollers[9,10]. The pitch of screw ribs on the front section was large, it is because that the corn stalk was pushed into the snapping gap by real tooth. A large pitch can accelerate the movement of corn stalks, so as to reach the body portion. Then the pitch became small gradually so as to reduce the movement speed towards backward, but the speed towards downward remained constant, so that corn ears can be picked before corn stalks reach the end of cut portion, and the whole corn stalk could be pulled out of cut portion[2] to avoid blocking.



A. Outer snapping roller B. Inner snapping roller 1. Tapering portion
2. Body portion 3. Cut portion 4. Variable screw pitch ribs

Figure 1 Variable screw pitch ribs snapping rollers

2.2 Analysis of cutting angle

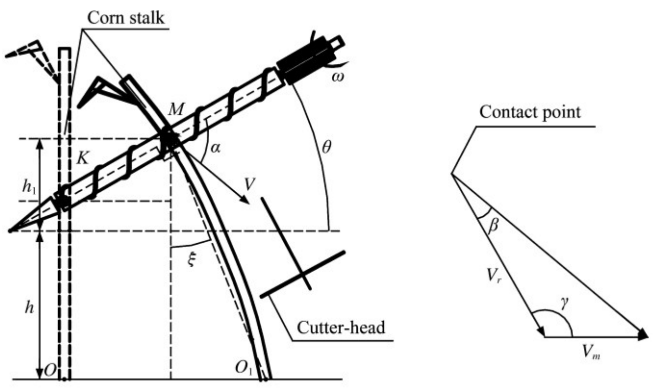
Standing residue processes should leave the bottom part of each corn stalk. When a corn harvester is working, the corn stalk is dragged by snapping rollers, and according to the relativity of movement, the corn stalk moves towards back and down relative to the corn harvester, thus the corn stalk has a deflection deformation since it entered the gap between two snapping rollers[11]. If the cutter-head (as shown in Figure 2, it is a rotating knife, and its shape is round) cut the corn stalk horizontally, there will be a sharp point on the transect after the corn stalk rebounded vertically, because the transect is not a plane, it will do serious harm to the rubber tires of tractors in the following works[12]. The best condition is that the cutter-head can cut corn stalks perpendicularly, thus transect could be a plane after it rebounded vertically[13,14]. As shown in Figure 2, in order to simplify the analysis process, only one snapping roller was taken into consideration. Dragged by snapping rollers, the corn stalk deformed from broken line (vertical) to solid line (partly curved). The contact point of the corn stalk and the snapping roller moved from K to M (Figure 2a). As shown in Figure 2b, the instantaneous velocity V of the contact point is a sum speed of two component velocities, one is the feeding velocity V_m of the corn stalk relative to the corn harvester (actually, V_m is the harvester's forward speed, but the assumption was the corn harvester was motionless, the corn stalk moves towards the corn harvester), and the other one is the linear velocity V_r of the snapping roller.

$$V_r = \omega r \tag{3}$$

$$\gamma = \frac{\pi}{2} + \theta \tag{4}$$

$$V = \sqrt{V_r^2 + V_m^2 - 2V_r V_m \cos\gamma} \tag{5}$$

where, V_r is the linear velocity of snapping roller, m/s; ω is the rotary speed of snapping roller, r/min; r is the radius of snapping roller, mm; γ is the angle between the linear velocity of snapping roller and the ground, (°); θ is the angle between the snapping roller and the ground, (°); V_m is the feeding velocity that the corn stalk relative to the corn harvester, m/s; V is the instantaneous velocity of the contact point, m/s.



a. Relative movement between snapping roller and corn stalks b. Velocity diagram of the contact point

Figure 2 Sketch map of effect between corn stalks and the snapping roller

Because the corn stalk has a deflection, it is difficult for the cutter-head to cut the corn stalk perpendicularly, but if the cutter-head can be perpendicular with line segment O_1M in Figure 2, it can achieve the best transect relatively. So it is important to know the angle ξ in Figure 2.

$$\beta = \arccos\frac{V_r^2 + V^2 - V_m^2}{2V_r V} \tag{6}$$

$$\alpha = \frac{\pi}{2} - \beta \tag{7}$$

$$h_1 = \int_0^t V\cos\alpha * \sin\theta dt \tag{8}$$

$$\xi = arc\cot\frac{\int_0^t V\cos\alpha * \sin\theta dt + h}{\int_0^t [V\cos(\alpha - \theta) - V_m]dt} \tag{9}$$

where, β is the angle between the linear velocity of the snapping roller and the instantaneous velocity of the contact point, (°); α is the angle between the instantaneous velocity of the contact point and the axis of the snapping roller, (°); h is height above the ground of the contact point when the corn stalk enters the snapping region of the snapping roller, mm; h_1 is the height gain of the contact point in the vertical direction after a certain time, mm; ξ is the angle between line segment O_1M and the vertical direction in Figure 2, (°).

The deflection deformation of corn stalks will take place immediately after corn stalks entered the body portion. In Figure 2, according to the relativity of movement. V_m is the relative velocity between the corn stalk and the corn harvester, and line segment OO_1 is the feed amount for a very short period, in other words, line segment OO_1 is the harvester forward distance during this very short time. Finally, according to the velocity of corn harvester, as well as the radius of snapping roller and its rotary speed, we could assess the best value of angle ξ. Another point should be mentioned was the definition of cutting angle, the cutting angle of the cutter-head in Figure 2 was positive value, and the cutting angle was 0° when it was horizontally cutting.

2.3 Experiment

2.3.1 Field imitating experiment

Two experiments were conducted in this study, one was the experiment of snapping rollers with variable screw pitch ribs, and the other one was standing-residue cutter. As we all know, corn harvesting time is very limited, and it is less than one month in Northeast China, so before doing the field experiment, a field imitating experiment was conducted before the corn was ripe completely so as to save some time and avoid some errors. In order to simulate standing corn stalks, we designed a rail to hold corn stalks, and the space between each stalk was 200 mm, as shown in Figure 3.

Figure 3 Field imitating experiment

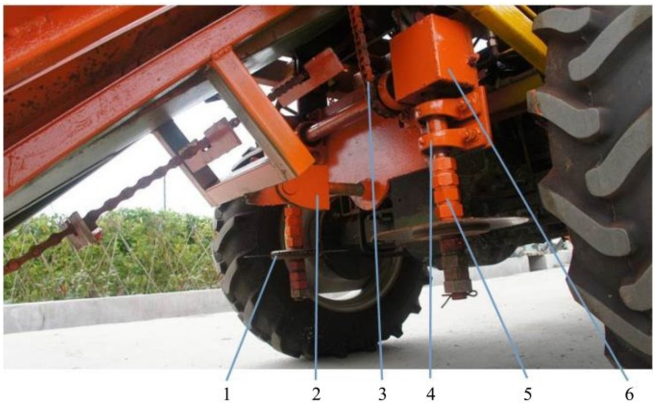
The main purpose of this experiment was to testify the basic snapping function of the snapping rollers and the basic cutting function of standing-residue cutter. The detail experimental treatment could be found in the appendix video.

2.3.2 Field experiment

After manufacturing this snapping rollers and the cutter, they were mounted to a 4YWL-2 corn harvester (The 4YWL-2 corn harvester was produced by Jilin University). The experiment was conducted on October 8, 2013 in the Agricultural Experiment Station of Jilin University, as shown in Figure 5. The experimental plot was 300 m long and 200 m wide; the corn variety was Jidan209 which is a common variety in Jilin Province of China in recent years.

The first experiment was to test the snapping roller. Two 4YWL-2 corn harvesters were applied in this experiment, the one with variable screw pitch rib snapping rollers (VSR), and the other with fixed screw pitch rib snapping rollers (FSR). The first pitches of screw rib on both snapping rollers are the same, it is 15 cm as common snapping rollers. In this experiment, the same driver who drove these two corn harvesters one by one. The driver started driving the harvester to a stable speed which was about 2 km/h, then the driver accelerated its speed by the acceleration of 0.05 m/s^2 until one pair of snapping rollers occurred blocking or both two pairs of snapping rollers occurred blocking. Ten replicates were conducted on each corn harvester during this experiment, meanwhile, a cab-speedometer was used to record the speed when the blocking occurred. The average speed of ten replications was the mean speed when blocking occurred.

The second experiment was to test the standing residue cutter. According to the research result of Jia et al.[3], the height of standing corn residue can influence the control effect of soil wind erosion, and the minimum height should be 300-500 mm depends on the soil texture. But the cutting height could not be equal to the standing-residue height (SRH) (hereafter referred to as 'SRH') in real working condition[6], so the cutting height was designed from 250 mm to 650 mm in order to compensate this error, and the cutter was shown in Figure 4.



1. Cutter-head 2. Adjust mechanism of cutting angle 3. Driving chain 4. Bearings 5. Mechanism to adjust cutting height 6. Reverse gear box

Figure 4 Cutter with adjustable cutting angle of the disks

In this experiment, optimum working conditions of the corn harvester was selected: its forward speed was about 2 km/h, the angle between the snapping roller and the ground was 40°, and the rotary speed of the snapping roller was about 400 r/min[6]. There were two dominating dependent parameters in this experiment:

cutting ratio which was defined by Equation (10) and SRH. The dominating independent variables in this experiment were the cutting height and cutting angle.

Figure 5 Field experiment

There were two purposes in the cutting experiment, the first was to test the cutting ratio, and the second was to explore the relationship between cutting height and SRH. In order to test the cutting ratio, the cutting height of this cutter varied from 300 mm to 500 mm with increments of 20 mm, and the cutting angle varied from 15° to 0° with the decrements of 3°. Each experimental treatment was a combination of cutting height and cutting angle, so there were 66 experimental treatments totally. Subsequently, we calculated the cutting ratios δ by measuring every corn stalk in each experimental treatment.

$$\delta = \frac{m}{n} \times 100\% \tag{10}$$

where, δ is the cutting ratio, %; m is the stalk population which were cut off completely; n is total stalk population of each working treatment.

As a final note, cutting height were measured from the center of the cutter-head, the SRH was measured from the highest point in transect.

In order to determine whether there was a significant variation about cutting ratio or SRH, z-test was used as a statistical analysis method. Because the data of experimental treatments were large enough according to principle of statistics, the population variance was represented by the moment estimation of sample variance.

3 Results and discussion

3.1 The experiment of VSR

In terms of the corn harvesters in the experiments, all the working parameters were the same except for the type of snapping rollers. The experimental result was shown in Table 1.

Table 1 The mean speed when blockings occurred

Type	Mean speed/km/h
FSR	4.85
VSR	7.6

Table 1 illustrated that the blocking occurred at the mean working speeds of 4.85 km/h and 7.6 km/h on the corn harvesters with FSR and VSR respectively, which indicated that the VSR could improve working efficiency by 56.7% compared to FSR. The experimental result was accordance with the previous analyses, and the experimental result showed that VSR can avoid corn stalk blockings effectively compared to FSR.

The blocking in the gap between two snapping rollers was a main problem for corn harvester, especially small corn harvester which had poor manufacturing qualities. One similar research came from Wang[10], who used differential screw pitch ribs on the snapping rollers, but only two constant screw pitch ribs were used. The biggest advantage of the snapping roller presented in this paper was it has a continuously varying pitches, so the screw ribs on the snapping roller does not have inflection points; in terms of mathematical principle, the curve could be derivation, so this design can reduce the vibration of corn ear, which resulted in reduction of grain loss when the corn ear got over-ripe[9].

3.2 The experiment of cutting ratio

Both cutting height and cutting angle had influences on cutting ratio (Figure 6). While the cutting height was fixed, the cutting ratio's mean value was calculated by Equation (11). While the cutting angle was fixed, the cutting ratio's mean value was calculated by Equation (12). There were 11 fixed cutting heights in this experiment, the starting cutting height was 300 mm, the ending cutting height was 500 mm, and the increment was 20 mm. Under the cutting heights from 300 mm to 500 mm, the average cutting ratios were 82.61%, 83.86%, 85.15%, 86.55%, 87.2%, 90.7%, 91.01%, 92.48%, 93.28%, 93.73% and 93.33% respectively. The average cutting ratio had a significant increase (p<0.05) along with the increasing of cutting height.

There were 6 cutting angles in the experiments, the starting cutting angle was 15°, the ending cutting angle was 0°, and the decrement was 3°. Under the cutting angles which from 15° to 0°, the average cutting ratios were 88.71%, 88.76%, 88.83%, 88.9%, 88.99% and 89.08% respectively. The average cutting ratio had a significant increase (p<0.05) along with the decreasing of cutting angle.

$$\varepsilon_{\varphi} = \frac{1}{6}\sum_{\omega}\delta_{\varphi,\omega} \tag{11}$$

where, ε_{φ} is mean cutting ratio with a fixed cutting height of φ, %; $\delta_{\varphi,\omega}$ is cutting ratio of a specific experimental treatment, %. This experimental treatment was combined a cutting height of φ and a cutting angle of ω.

$$\varepsilon_{\omega} = \frac{1}{6}\sum_{\varphi}\delta_{\omega,\varphi} \tag{12}$$

where, ε_{ω} is mean cutting ratio with a fixed cutting angle of ω, %; $\delta_{\omega,\varphi}$ is cutting ratio of a specific experimental treatment, %. This experimental treatment was combined a cutting angle of ω and a cutting height of φ.

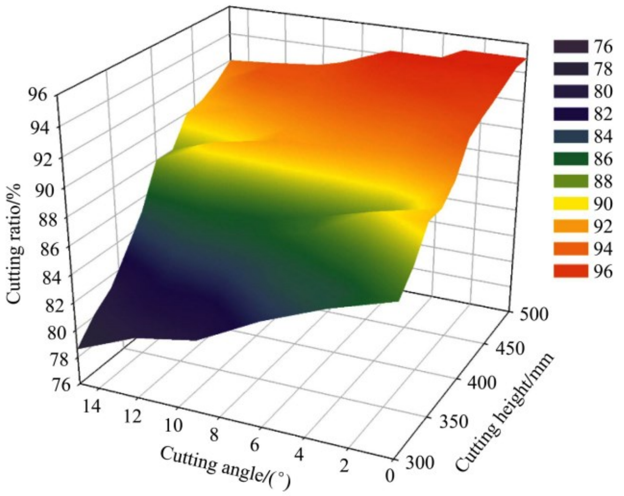


Figure 6 Relationship among cutting ratio, cutting height and cutting angle

Higher cutting height and smaller cutting angle could contribute to larger cutting ratio (Figure 6), and vice versa. The reason was while the cutting height increased and cutting angle decreased, the height of cutting point (defined as the contact point of the cutter-head and the corn stalk) increased. The key point that should be mentioned was that the bottom part of corn stalk was thicker than the upper part, in other words, it was easier to cut the upper part than the bottom part, thus the higher cutting point, the bigger cutting ratio. In addition, as shown in Figure 2, the smaller of cutting angle, the closer to sliding-cutting rather than chopping-cutting, and smaller force needed of sliding-cutting than chopping-cutting[15], which resulted in larger cutting ratio when cutting angle decreased.

3.3 The experiment of average SRH

Both cutting height and cutting angle had influence on average SRH (Figure 7). While the cutting height was fixed, the average SRH was calculated by Equation (13). While the cutting angle was fixed, the average SRH was calculated by Equation (14). Similar as cutting ratio, under the cutting angle which from 15° to 0°, the average SRHs were 401 mm, 404 mm, 407 mm, 410 mm, 413 mm and 416 mm respectively. The average SRH had a significant increase (p<0.05) along with the decreasing of cutting angle.

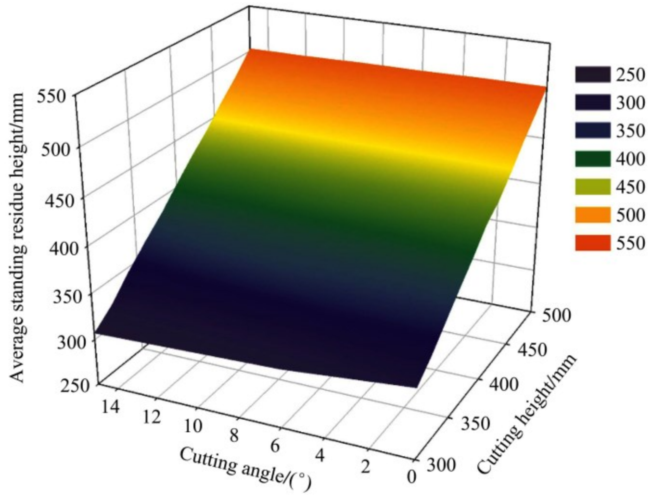


Figure 7 Relationship among average SRH, cutting height and cutting angle

Under the cutting height from 300 mm to 500 mm, the average SRH were 314 mm, 332 mm, 354 mm, 373 mm, 388 mm, 410 mm, 426 mm, 445 mm, 465 mm, 483 mm and 504 mm. It was obvious that the average SRH increased along with the increasing of cutting height.

$$L_{\omega} = \frac{1}{6}\sum_{\varphi}H_{\omega,\varphi} \tag{13}$$

where, L_{ω} is mean value of SRH with a fixed cutting angle of ω, mm; $H_{\omega,\varphi}$ is mean value of SRH with a specific experimental treatment, mm. This experimental treatment was combined a cutting angle of ω and a cutting height of φ.

$$L_{\varphi} = \frac{1}{11}\sum_{\omega} H_{\varphi,\omega} \tag{14}$$

where, L_{φ} is mean value of SRH with a fixed cutting height of φ, mm; $H_{\varphi,\omega}$ is mean value of SRH with a specific experimental treatment combined a cutting height of φ and a cutting angle of ω, mm.

During cutting processes, corn stalks were pulled by snapping rollers which were rotating at high-speed, and moved downward rapidly. At the same time, they were pushed laterally by the cutter-heads. But they will rebound after been pushed due to corn stalks have a bending resistance[16,17], thus the SRH can't be expected to be equal to the cutting height as a result of this rebounding property.

When the cutting angle was fixed, higher cutting height generally led to higher cutting point. Subsequently, there was less deflection deformation of corn stalks, and the stalk rebounded a smaller distance after been cut. So while the cutting height increased, the average SRH approached the cutting height. In other words, the difference between average SRH and cutting height became smaller. Similarly, if the cutting height was fixed, smaller cutting angle led to higher cutting point, which would result in the higher SRH. On the contrary, larger cutting angle always led to lower cutting point and lower SRH.

A corn field which has been worked by this novel corn harvester in this experiment was shown in Figure 8.

Figure 8 Operation effect

Bilbro and Fryrear[4] had already pointed out that standing millet residue was more effective than flat residue on controlling soil wind erosion, and Jia et al.[3] also certificated that standing corn residue could also be effective in controlling soil wind erosion in Northeast China. In additional, conservation tillage with standing corn residue could save the upper part of corn stalks which can be used as winter forage for livestock and biofuel for daily lives. This mode needs to retain a certain height of corn stalks, this research helped corn harvester to solve this problem. Desired SRH and plane-shaped transect of corn stalk can be obtained by adjusting the cutting height and cutting angle.

Both the grain breakage rate and impurity rate are low of horizontal roller corn harvesters; horizontal roller is a major snapping form of small or mid-sized corn harvesters. Studies have indicated that while utilizing reciprocating cutter to cut plants that have large haulm diameters, there are blank areas and concentrated areas in cutting zones, and the cutting table is often blocked[18,19]. Fortunately, rotary disc cutters have been found to be a suitable solution to this problem[20,21], so rotary disc cutter was adopted in this study.

4 Conclusions

Snapping-roller blocking is a serious limitation on working efficiency for corn harvester. The VSR solved this problem partially; compared to FSR, VSR could improve working efficiency by 56.7%.

A novel residue cutter was developed in order to cooperate with standing corn residue. The average cutting ratio had a significant increase (p<0.05) along with the decreasing of cutting angle. The average SRH had a significant increase (p<0.05) along with the decreasing of cutting angle. A plane transect of the corn stalk is ideal for the following work, but the cutting ratio should be decreased as a side effect. In order to obtain a plane transect, and do not decrease cutting ratio at the same time, further research still is needed.

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