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Factors Affecting Performance of Rotary Impact-Type Threshers for Sesame and Perilla Harvesting

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Abstract

Purpose: The purpose of this study was to analyze the performance factors of a rotary impact-type thresher to develop a sesame and perilla thresher, specifically to analyze the cut length of the stems and the threshing rates based on the relationship between the blade velocity and feeding speed. **Methods:** The materials were dried within a range of 12.3–13.0% to test the impact cut by bending. The cut lengths of the perilla and sesame stems were categorized in 6 ranges (~7.0, 7.1–10.0, 10.1–13.0, 13.1–16.0, 16.1–20.0, 20.1– (cm)). For testing the cut length and threshing rate, the upward-rotating blade velocity was varied as 11.0 m/s, 13.5 m/s, and 22.3 m/s. Feeding speeds were changed from 0.1 m/s to 2.2 m/s by the inverter connected to the feed motor. The feed rate and threshing rates without cover-casing were evaluated with the factors of thresher testing. **Results:** The mean cut length of the stem decreased as the blade velocity increased and/or the feeding speed decreased. As the feed rate increased up to 17.5 g/s, the cut length distributions showed no significant difference. The threshing rate was 98.9% for sesame, and flexible according to the blade velocity and feeding speed of the perilla. **Conclusion:** Feeding material too fast could produce longer cut stem segments, therefore, a feeding speed less than 2.2 m/s is recommended. A blade velocity of 13.5 m/s is preferable for both sesame and perilla with regard to cut length and threshing rate.

Keywords: Cut length, Impact bending, Perilla, Rotary threshing, Sesame

Introduction

Currently, threshing machines dedicated to sesame and perilla are rarely commercialized. Instead, similar machines such as a soybean thresher are used. However, these threshers do not take into account the physical characteristics of sesame or perilla, and are therefore not widely used. Traditionally in Korean farmhouses, the flail tool has been used to thresh sesame and perilla grains. It has rotatable rods attached to a long stick and strikes the crop stems on the floor (Fig. 1 (a)). This impacting principle was adopted in this study to develop a thresher exclusively for sesame and perilla. By using this principle, a rotary impact-type thresher for soy beans was recently developed (SAITO, 2016). Rotary impact-type threshers have a simple structure compared to conventional threshers, such as drum, spike tooth, and concave equipped threshers, and it is also possible to avoid the difficult cleaning process due to excessive crushing. The rotary impact-type thresher could cause damage to the grains by the blade strikes, but small grains such as sesame or perilla are typically damaged less (Kirkkari et al. 2001, Špokas. et al. 2008). Figure 1 (b) shows a schematic diagram of the commercial rotary impact-type thresher.

Stems could wind around the rotating blades of a rotary impact-type thresher if they are not cut, so it is necessary to cut stems to an appropriate length. However, too many chips make subsequent processes, such as screening and cleaning, difficult. Stem cut length can be varied according to the feeding distance of the stem for a stroke calculated by blade velocity and feeding speed. Physical properties of the materials also affect the cut length (Lisowski, et al.

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(a) Traditional sesame and perilla thresher (b) Device adopting flail principle

Figure 1. Traditional flail tool and schematic diagram of rotary impact-type thresher.

2009). Studies that analyze force or energy for rotary impact threshing are very rare, but there are some that could be referred to in the field of impact-cutting of grasses and impact-bending of laminates.

Sonderegger and Niemz (2004) tested the strength, bending, and Young's modulus on the basis of eigen-frequency and sound velocity on small clear wood specimens of Norway spruce wood. A model of the stem as a uniform cantilever was developed in order to investigate the impact cutting process. For example, McRandal and McNulty (1978) conducted theoretical and experimental investigations on impact cutting processes. For impact cutting with a high blade speed, it seems reasonable to picture the stem as a vibrating beam in which only inertia and bending effects are considered. Therefore, the differential equation governing the free vibration of a uniform beam (Church, 1963) is used. Chattopadhyay and Pandey (2001) developed a mathematical model to estimate the impact cutting energy and power requirement using crop and machine parameters when harvesting forage crops with flail-type cutters. Investigations of the distribution in length of energy crops broken up in a chopping unit of the forage harvester were also performed (Lisowski, 2009). The Geometric Mean Method and the Rosin-Rammler Method were used to analyze the length distribution of several crops. The results showed that connectivity between the two methods was high (R=0.994). Moreover, Abrate (2001) presented various models available for analyzing the impact dynamics for selecting an appropriate model for each particular case. Naik et al. (2000) studied the behavior of woven-fabric composite plates under transverse low-velocity impact employing an analytic model based on a modified Hertz law and three- dimensional (3D) numerical model.

A study on the impacting principle is needed before theoretical modeling. This study provided the basic data and concept for developing a rotary impact-type thresher in terms of cut length of the stems and threshing rates.

The purpose of this study was to analyze the performance factors of a rotary impact-type thresher to develop a sesame and perilla thresher, specifically to analyze the cut length of the stems and the threshing rates based on the relationship between the blade velocity and feeding speed.

Materials and Methods

Materials

For experiment materials, we used sesame from the field, dried for ten days after harvesting (12.3% moisture

Table 1. Physical properties of sesame used for the experiments

Whole height (cm)	Pod numbers	Stem weight (g)	Total pod weight (g)	Grain weight from 10 pods (g)	Moisture content (%)	Note
112.80	50	7.03	6.61	1.00	12.3	10 days after harvesting

Table 2. Physical properties of perilla used for the experiments

	Whole height (cm)	Pod numbers	Stem weight (g)	Total pod weight (g)	Pod numbers/ height (number/cm)	Moisture content (%)	Note
Type 1	120.20	345.80	6.47	2.22	2.88	13.0	2 weeks after harvesting
Type 2	98.70	382.30	6.02	2.42	3.87	12.9	2 weeks after harvesting

content) (Table 1) and perilla from the field, dried for two weeks after harvesting (13.0% moisture content) (Table 2). Moisture contents decreased rapidly after harvesting each day but stabilized at the previously listed moisture contents. For the perilla test, two types of perilla from different fields in Chuncheon city were used. Type 1 had a longer stem than type 2.

Equipment

Figure 2 shows the schematic diagram of a rotary impact device and an experimental device which is equipped with a 2 Hp motor and power transmission (belt and pulley). The experimental device was designed for the cut length and threshing rate tests without casings. The rotator was equipped with four bar-type blades (Fig. 3). Feeding speed was controlled by the inverter, which controls the rotating speed of the feed motor in the range of 0–1800 rpm. A 2 Hp motor was used to drive the feed roller.

Method

The experiments were performed in two phases, which addressed the cut length of the stem and the threshing rate. The threshing rate could be varied depending on the blade velocity and feeding speed (Miu and Kutzbach, 2008). The cut lengths of the stems ranged between 4 and 30 cm as a whole and were categorized in six ranges (~7.0, 7.1–10.0, 10.1–13.0, 13.1–16.0, 16.1–20.0, 20.1–(cm)). Upward-rotating blade velocities were set at 11.0 m/s, 13.5 m/s, and 22.3 m/s by changing the pulley diameters. These velocities were chosen based on the velocity of the drum or rasp bar-type thresher (Jung et al., 1992). Feeding speeds were set at 0.1 m/s, 0.5 m/s, 1.1 m/s, and 2.2 m/s using the inverter connected to the feed motor. The detailed experimental design is presented in Table 3.

To investigate the effects of the feed rate, 5.2, 9.0, and 17.5 g/s feed rates were tested for the perilla stems. For the statistical analysis of the cut length, mean value, distribution, and skewness were examined. Negative skew indicates that the tail on the left side of the probability density function is longer or fatter than on the right side. Conversely, positive skew indicates that the tail on the right side is longer or fatter than the tail on the left side (Wikipedia, 2018). For statistical analysis, "Excel 2016 and R i386 3.4.3" were used.

Principle of impact cut by bending

When the stem is fed by the feed roller and reaches the

Figure 2. Schematic diagram (left) and device (right) of experiment.

Rotator specification	
Diameter	30 cm
Blade Number	4
Rotator length	23 cm
Blade thickness	0.4 cm

Figure 3. Rotator and blade picture (left) and specification (right).

Table 3. Experimental design

	Materials	Factors	Treatments	Note
Cut length	Sesame and Perilla	Blade velocity	11.0 m/s, 13.5 m/s, 22.3 m/s	Two factors factorial design
		Feeding speed	0.1 m/s, 0.5 m/s, 1.1 m/s, 2.2 m/s	
	Perilla	Feed rate	5.2, 9.0, 17.5 g/s Blade velocity 11.0 m/s	Feeding speed 1.1 m/s
Threshing rate	Sesame	Blade velocity	11.0 m/s, 13.5 m/s, 22.3 m/s	Two factors factorial design
		Feeding speed	0.1 m/s, 0.5 m/s, 1.1 m/s, 2.2 m/s	
	Perilla	Blade velocity	11.0 m/s, 13.5 m/s, 22.3 m/s	Two factors factorial design
		Feeding speed	0.1 m/s, 0.5 m/s, 1.1 m/s, 2.2 m/s	

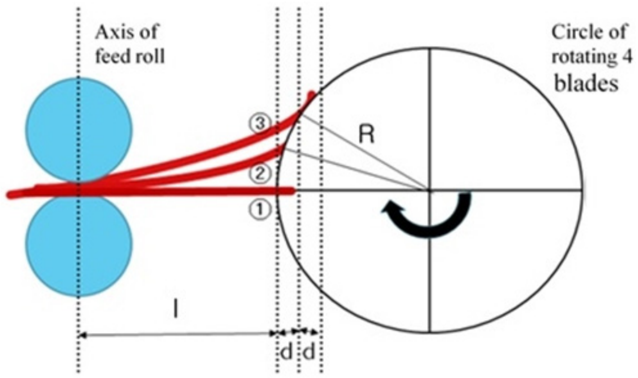


Figure 4. Diagram for principle of impact cut by bending

blade, a bending moment is generated by the stroke of the blade near the axis of the feed roller that holds the stem, and the stem is cut by the moment. The length of the cut stems is determined by the horizontal distance between the center of the feed roller and the striking blade. It was 8 cm long in the experimental device of this study. But the cut length varies according to the feeding speed and the blade velocity. The stems are cut by a single strike if the stress received by the impact is large enough to overcome the strength of the stem, but depending on the tensile strength of the stem (for example, the tensile strength of the perilla is stronger than the sesame), it is cut by two or more strokes. As shown in Figure 4, if a stem is not cut by a single stroke at position (1), it is moved to position (2) or (3) by the blade, and receives not only a bending moment but also tensile force, which increases as the number of strokes increases, because the striking angle of the blade changes.

Calculation of the cut length of the stem according to stroke number

Forward length of the stem for a stroke interval of the blade, "d" in Figure 4 can be expressed as a function of blade velocity and feeding speed.

$$d = 2\pi * R * Fs / (Bv * N) \tag{1}$$

where d: Forward length of the stem for a stroke interval of the blade,
R: Radius of blade rotator,
Fs: Feeding speed,
Bv: Blade velocity,
N: Blade numbers.

Table 4 shows the calculated values of "d" using the equation (1).

Cut length of the stem, L, is calculated using the following equations. For the calculation of cut length by the first stroke,

$$L = l + d \tag{2}$$

where L: Cut length of the stem,
l: Horizontal distance between the center of the feed roller and the striking blade.

First stroke occurs after the stem travels from the feed roller and past the blade. The forward advancing length exceeding the blade might be randomized in the range of 0 − d, but in this study, the maximum value of forward distance per stroke was taken.

From the second stroke, it increases by "d" at each stroke.

Table 4. Forward length of the stem for a stroke interval of the blade (cm)

Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
0.1 m/s	0.22	0.18	0.10
0.5 m/s	1.10	0.90	0.50
1.1 m/s	2.30	1.94	1.16
2.2 m/s	4.60	3.84	2.32

Table 5. Theoretical cut length of the stem (cm)

Blade velocity	11.0 m/s			13.5 m/s			22.3 m/s		
Feeding speed	Cut at 1st stroke	Cut at 2nd stroke	Cut at 3rd stroke	Cut at 1st stroke	Cut at 2nd stroke	Cut at 3rd stroke	Cut at 1st stroke	Cut at 2nd stroke	Cut at 3rd stroke
0.1 m/s	8.22	8.44	8.66	8.18	8.36	8.54	8.10	8.20	8.30
0.5 m/s	9.10	10.20	11.30	8.90	9.80	10.70	8.50	9.00	9.50
1.1 m/s	10.30	12.60	14.90	9.94	11.88	13.82	9.16	10.32	11.48
2.2 m/s	12.60	17.20	21.80	11.84	15.68	19.52	10.32	12.64	14.96

For the second stroke, $L = 1 + 2d$ (3)

For the third stroke, $L = 1 + 3d$ (4)

Table 5 shows the theoretical cut lengths calculated using the equations (2),(3) and (4).

Results and Discussion

Mean cut length and length distribution of sesame and perilla

Mean cut length and comparison of theoretical and experimental stroke number for sesame stem

Table 6 and Figure 5 show mean sesame cut lengths according to the blade velocity and feeding speed. The mean cut length of the stem decreased as blade velocity increased and/or feeding speed decreased.

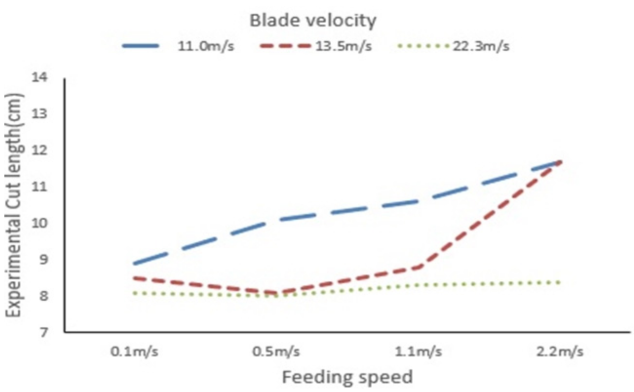


Figure 5. Diagram showing the trend of variance with the data in Table 6.

Table 6. Mean cut lengths according to the blade velocity and feeding speed for sesame (cm)

Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
0.1 m/s	8.9	8.5	8.1
0.5 m/s	10.1	8.1	8.0
1.1 m/s	10.6	8.8	8.3
2.2 m/s	11.7	11.7	8.4

As illustrated in Figure 5, mean cut lengths do not vary much according to the feeding speed for a high blade velocity (22.3 m/s), however, cut length increases with feeding speed increase for low blade velocity (11.0 m/s).

Experimental cut lengths were compared to theoretical values. Theoretical cut lengths by the 1st stroke and 2nd stroke are shown in Figures 6 and 7, respectively. Except three cases (feeding speeds of 0.1 and 0.5 m/s at a blade velocity of 11.0 m/s and a feeding speed of 0.1 m/s at a blade velocity of 13.5 m/s), 2nd stroke theoretical cut length differs more from the experimental cut length compared to 1st stroke theoretical cut length. Experimental cut lengths have a range of difference from -18.6 to 2.9% with the 1st stroke theoretical cut length, but with 2nd stroke theoretical cut length, the range was -33.5 – 5.5%. Therefore, it is theorized that the stem cutting occurred with the 1st stroke at a high blade velocity, but at low blade velocity and low feeding speed (above three cases), it occurred on the 2nd stroke. Considering that the maximum forward distance exceeding the blade was taken at the first stroke when we calculated the theoretical cut length, the difference between 1st stroke theoretical cut length and experimental cut length would be less.

Cut length distribution for sesame stem

High feeding speed produces longer or uncut segments of the stems at low blade velocities (11.0 or 13.5 m/s), but decreases at a high blade velocity (22.3 m/s) (Table 6 and Fig. 8). Table 7 shows an asymmetric degree (skewness

Table 7. Skewness value of the length distribution for sesame

Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
0.1 m/s	0.283286	0.301993	-0.15352
0.5 m/s	2.19309	2.03922	0.0274
1.1 m/s	1.411549	1.192071	-0.22835
2.2 m/s	2.032358	1.593969	0.775071

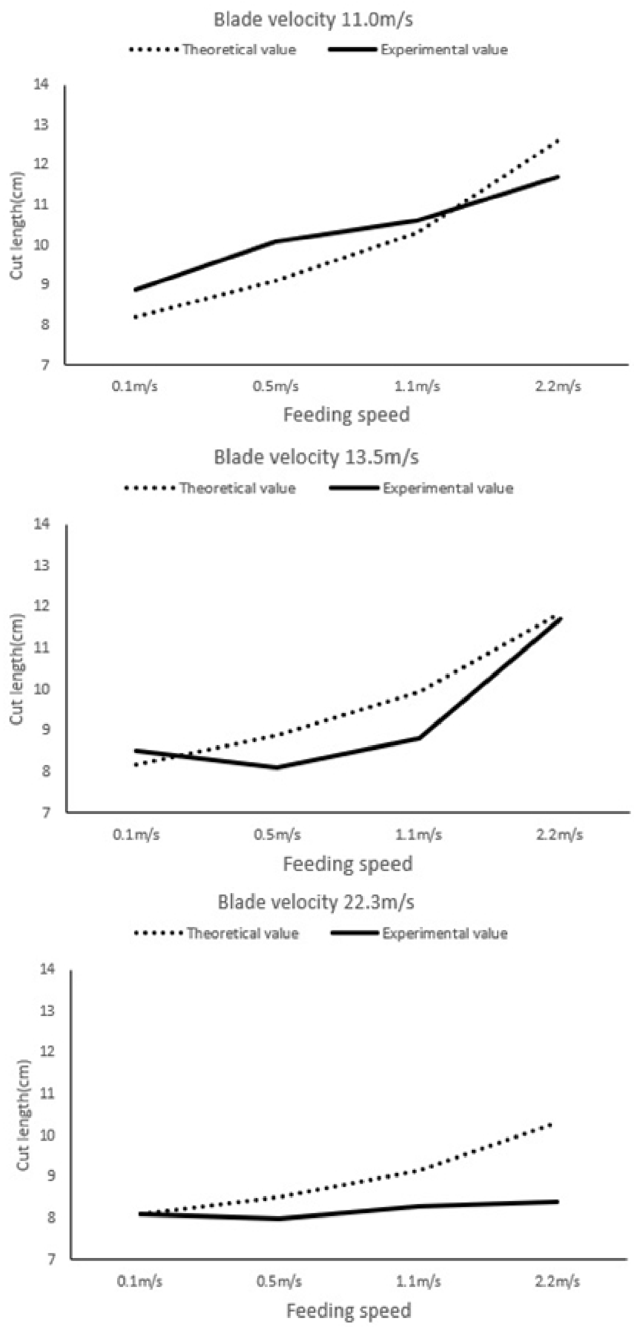


Figure 6. Comparison of experimental cut length with 1st stroke theoretical cut length.

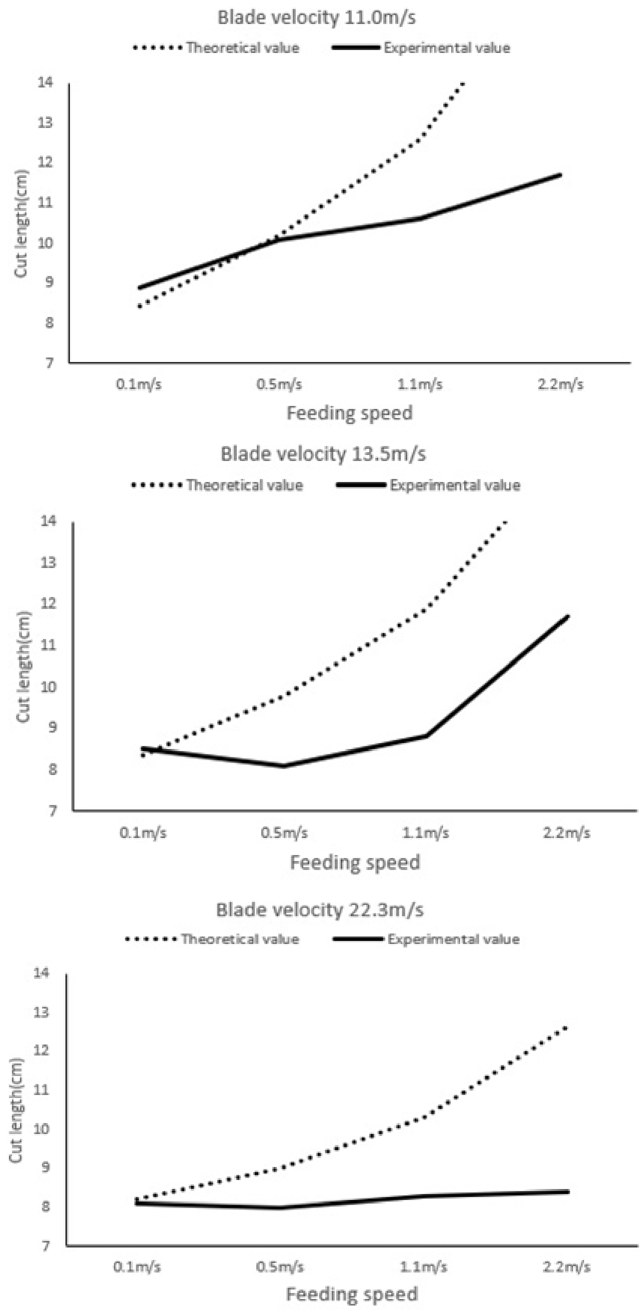


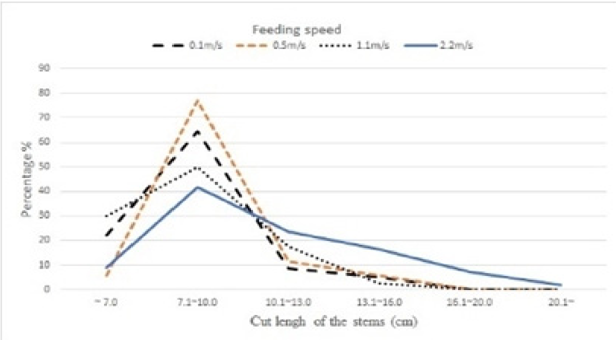
Figure 7. Comparison of experimental cut length with 2nd stroke theoretical cut length.

index) of the distribution. Generally, the tails of the curve were on the right side (positive index). Asymmetric degrees were high at low blade velocities (11.0 m/s and 13.5 m/s). This means that uncut or longer cut length segments increased under these conditions.

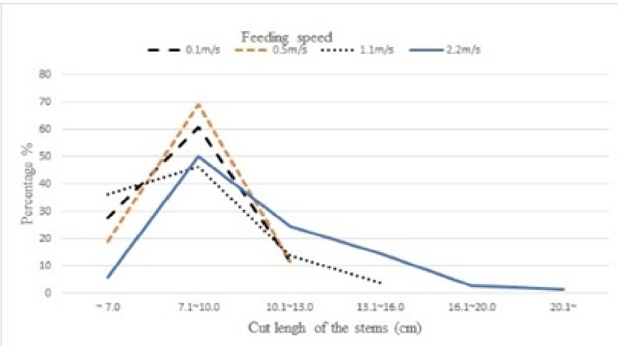
Mean cut length and distribution for perilla

Similarly, the result of the experiments for the perilla are shown in Tables 8 and 9 and Figure 9. The mean cut lengths of perilla are longer than the cut lengths of sesame. This could be due to the tensile strength difference and the stem physical properties.

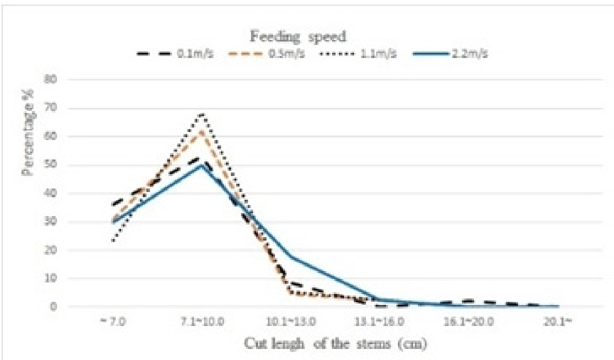
Similar to sesame, skewness has the general trend of moving in the symmetric direction as the blade velocity increases. At low blade velocities (11.0 m/s and 13.5 m/s), asymmetric degrees were high, but the difference



(a) Blade velocity: 11.0 m/s

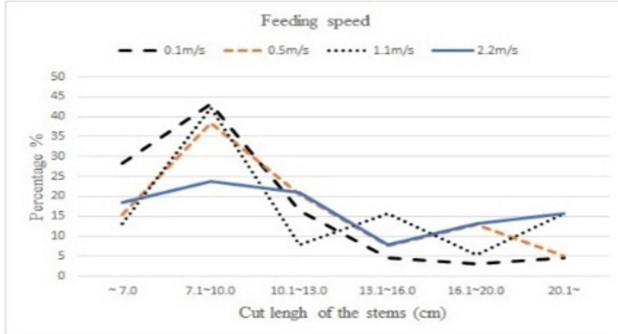


(b) Blade velocity: 13.5 m/s

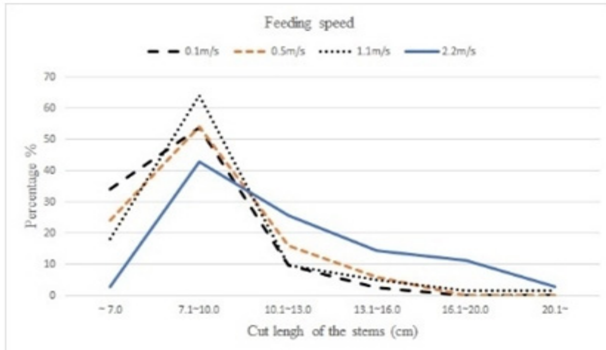


(c) Blade velocity: 22.3 m/s

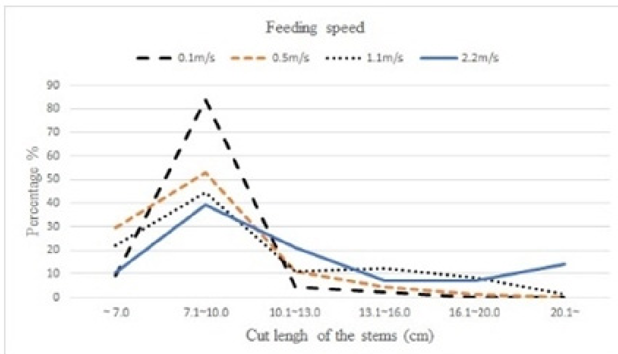
Figure 8. Length distribution according to the blade velocity and feed speed for sesame.



(a) Blade velocity: 11.0 m/s



(b) Blade velocity: 13.5 m/s



(c) Blade velocity: 22.3 m/s

Figure 9. Length distribution according to the blade velocity and feed speed for perilla.

of the skewness values between conditions were smaller than for sesame (Table 9).

The results of the test for cut length of the sesame and perilla are similar to the results of the previous research

Table 8. Mean cut lengths according to the blade velocity and feed speed for perilla (cm)

Type	Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
Type 1	0.1 m/s	9.30	9.27	8.33
	0.5 m/s	13.05	9.52	8.63
	1.1 m/s	12.91	12.86	9.49
	2.2 m/s	17.07	12.82	12.44
Type 2	0.1 m/s	10.41	9.56	7.71
	0.5 m/s	10.93	11.68	9.14
	1.1 m/s	14.07	11.90	12.33
	2.2 m/s	15.48	12.73	11.96

Table 9. Skewness value of the length distribution for perilla

Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
0.1 m/s	0.920521	0.492198	0.165285
0.5 m/s	1.75378	1.533544	0.726494
1.1 m/s	1.511572	1.48812	0.814508
2.2 m/s	1.710929	1.119133	1.620299

on the distributions of the cut length for energy plants, which were cut by chopping (Lisowski, et al. 2009). However, the mean cut lengths for sesame and perilla are much higher than the mean cut lengths resulting from chopping.

Effect of feed rate on length distribution of perilla stem

The experimental results of the length distribution according to the feed rate (5.2, 9.0, and 17.5 g/s at a blade velocity of 11.0 m/s and feeding speed of 1.1 m/s) are shown in Figure 10. As the feed rate increases up to 17.5 g/s, the cut length distributions showed no significant difference in 95% confidence level.

Threshing rate of impact-type thresher for sesame and perilla

Threshing rates of the sesame by blade impact are shown in Table 10. There was not a large difference in all test conditions without cover-casings, as shown in Figure 1 (b). The threshing rate was 98.9% on average without cover-casings for the sesame.

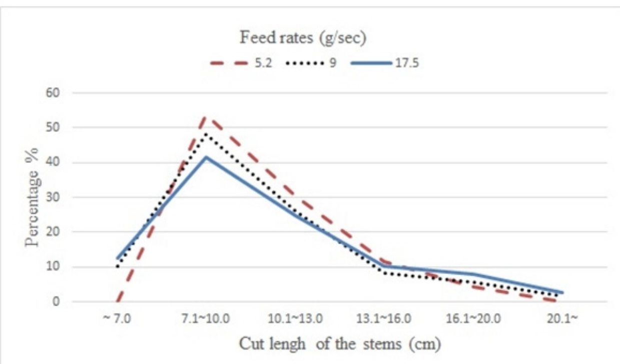


Figure 10. Length distribution according to the feed rates (5.2, 9.0, 17.5 g/s) for perilla.

Table 10. Threshing rate of sesame (%)

Feeding speed \ Blade velocity	11.0 m/s	13.5 m/s	22.3 m/s
0.1 m/s	98.7	99.0	99.0
0.5 m/s	98.7	99.1	98.7
1.1 m/s	99.5	99.1	99.5
2.2 m/s	98.0	99.0	99.0

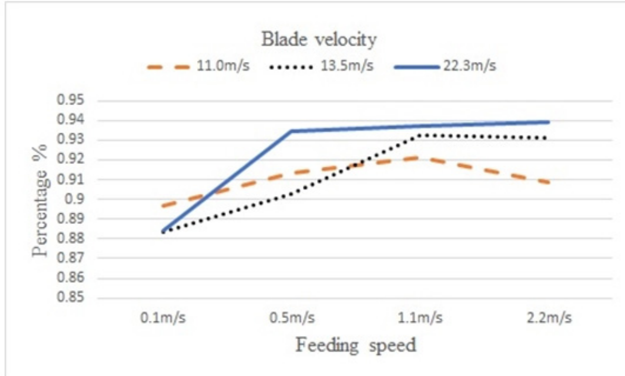


Figure 11. Threshing rates for perilla according to blade velocity and feeding speed.

The threshing rate was flexible according to the blade velocity and the feeding speed for the perilla. The recommended feeding speed and the blade velocity for the threshing rate of perilla were 1.1 m/s and 13.5 m/s, respectively (Fig. 11).

The threshing rate in other research for the sesame thresher was 90.3–98.5% at 1st threshing depending on the threshing methods (Lee and Kim, 2009). Therefore, the results of the experiments for threshing rates in this study could be effectively evaluated. The threshing rates with cover casings would increase more, so further study is needed.

Conclusions

In this study, the cut length of the stems and the threshing rates of sesame and perilla were analyzed based on the relationship between the blade velocity and feeding speed. The stroke number needed for cutting sesame stem was 1–2 strokes for a moisture content of 12.3%. The mean cut length of perilla was longer than for sesame by up to 4.8 cm. This means more strokes were needed to cut the perilla stem than the sesame stem.

The mean cut length of the stem decreased as the blade velocity increased and/or the feeding speed decreased. The threshold cut length of about 8 cm is the shortest distance between the feed roll axis and the blades, meaning chips that could hinder the cleaning process were not produced. Feeding the stems too fast could produce longer cut stem segments, so a feeding speed less than 2.2 m/s is recommended. There was no difference between the cut lengths in terms of the feed rates at the confidence level of 95%, but if too many stems were inserted, there would be a difference.

For very dry sesame, no matter the blade velocity, feeding speed, and casings, threshing rates were very high. But for the high moisture content sesame, further study is needed. For the perilla, threshing rates varied depending on the blade velocity and feeding speed, but were over 88% in all conditions. The preferable feeding speed and blade velocity for the threshing rate of perilla were 1.1 m/s and 13.5 m/s, respectively. With casings, it could be possible to increase the threshing rate.

Considering the cut length and threshing rate, 13.5 m/s of blade velocity was preferable for both sesame and perilla.

Conflict of Interest

The authors have no conflicting financial or other interests.

Acknowledgement

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