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Technical Note

Development and Performance Test of a Simulation-Based Tractor-Attachable Wind-Blast-Type Onion Stem Cutting Machine

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Abstract: Stem cutting process of many steps in onion farming involves the least supply of machines. Machines developed in foreign countries are not suitable owing to the geographic characteristics of Korea; it is necessary to develop customized machines. Therefore, in this study, a tractor-attachable blast-type onion stem cutting machine was developed to address these issues. To determine the installation angle of a detachable blade with a 300-mm length, 115-mm width, 5-mm thickness, and a cutting angle of 45° at the tip, we compared the simulation results with the analysis results obtained by fabricating a simple experimental device. Despite small differences in values, the R^2 between the two results was found to be 0.99; if using a regression equation, they could be adequate for use in estimation. Moreover, by measuring the motor power consumption, wind speed, and high-speed camera shooting, the stem was raised, regardless of its water content, when the installation angle was greater than 30°. Motor power consumption could also be reduced when the installation angle was 30° rather than 40°. Therefore, the optimal cutter blade installation angle for the tractor-attachable blast-type onion stem cutting machine was confirmed to be 30°. The developed machine was tested at various rotating speeds. The best performance was obtained when the test was repeated thrice at a driving speed of 0.4 m/s. The remaining onion stem length averaged 9.98 cm, the standard deviation was 4.72 cm and the stem cutting rate was 96.8%.

Keywords: blade installation angle; onion stem cutting; performance test; tractor-attachable; wind-blast type

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1. Introduction

As of 2020, the mechanization rate of field agriculture in Korea was 61.9%, which has increased by approximately 15% over the past 10 years. However, this was still significantly lower than the mechanization rate of nonfield agriculture (98.6%). According to the Agricultural Machinery Usage Survey conducted by the Rural Development Administration (RDA) in 2020 [1], the low mechanization rate in field agriculture is due to the small amount of land ownership per person, which makes scaling up difficult. In fact, small-scale farmers with a land area of 0.3 hectares or less account for 85% of all farming households, making it difficult for them to purchase agricultural machinery. Additionally, unlike paddy fields with simple crops, such as rice in summer and wheat or barley in winter, field agriculture involves a larger number of crops, which is another factor delaying the mechanization of this type of farming. Ultimately, due to the lack of demand, related companies are also struggling to enter the field of agricultural mechanization [2].

Onion cultivation, a crop used in field agriculture, is an important crop that increases farmers' income during the winter off-season and has the highest consumption growth rate among vegetable crops. As consumer interest in diet and health continuously increases, the cultivation area and production volume of onions have also increased significantly. However, onion mechanization relies mainly on labor, except for operations such as plowing cessation, pest control, and plastic film covering. Mechanization is urgently required to increase efficiency, reduce production costs, and improve price competitiveness [3,4].

The total labor input per 10 acres for onion cultivation operations in Korea is 241.2 h, with seeding, transplanting, and harvesting operations having the highest proportion of manual labor input. These operations account for 42% of the total labor input cost, with seeding and transplanting at 30.8% and harvesting at 26.4%. During the harvesting operation, 30%, 60%, and 10% of the labor input are used for stem cutting, digging, and collection, respectively, requiring 27.6 h per 10 acres for stem cutting alone [5].

Harvesting largely depends on labor, and rural labor has rapidly declined from 2,843,318 farming households in 1970 to 53% of that in 2010. Additionally, rural labor has become elderly, and unskilled labor from urban areas is now involved in the work, which significantly lowers labor productivity. This phenomenon is a common issue across the entire agricultural industry; however, onion cultivation, such as rice farming, requires a significant amount of labor during transplanting and harvesting, creating a serious problem.

To address this issue, researchers have investigated the development of onion stem cutting machines. In foreign countries, these machines are commonly classified into three categories: roller-type [6], belt-type [7,8], and blast-type [9]. These machines have been developed and used successfully in various regions; however, challenges remain in their implementation owing to different onion farming systems and geographic characteristics. Domestic versions of these machines have also been developed; however, they still face issues, such as improper stem cutting and a shortage of wind to raise the stem. Therefore, further research is necessary to improve the design and implementation of onion stem cutting machines to increase the efficiency of onion harvesting [10].

The implementation of simulation technology for modeling product behavior has led to the increased use of simulation-driven design, optimization, and virtual testing. This trend has gained momentum as companies strive to reduce costs, increase innovation, and streamline production schedules. Companies can achieve competitive advantage by implementing simulation practices throughout the product development cycle. In addition, machine simulation is being explored as a method for detecting risk factors, such as machine interference and collisions, in advance and verifying the suitability of the design. Various studies have been conducted in this field, including those by Kim et al. [11], Son et al. [12], and Jung et al. [13].

This study aims to achieve several objectives related to the installation angle of a stem cutter blade in a stem cutting machine. First, a dynamic simulation software is used to analyze the optimal installation angle. Second, the simulation results are verified through experiments using specialized test equipment. Finally, the performance of the stem cutting machine is evaluated at different traveling speeds in various fields. Based on these objectives, this study seeks to provide valuable insights into the optimization of stem cutting machine design and performance.

2. Materials and Methods

2.1. Stress Analysis on Stem Cutter Blade in Simulation

Stem cutting tests were performed to determine the optimal installation angle for the stem cutter blade. The blade was manufactured by welding steel at angles of 0°, 10°, 20°, 30°, and 40° on both sides of the central axis, as shown in Figure 1. The cutting blade was 640 mm in diameter and 115 mm in width. The detachable blades on either side of the central axis were 300 mm long, 115 mm wide, and 5 mm thick. The cutting angle at the tip of the blade was 45°. The design was created using AutoCAD (AutoCAD 2016, Autodesk, San Rafael, CA, USA), and the simulation was performed using dynamic analysis software (RecurDyn, FunctionBay Inc., Seongnam-si, Republic of Korea). The rotational speed of the stem cutter blade was fixed at 540 rpm for both the simulation and experimentation.

To reduce the vibration of the device during the stem cutting test, the rotational speed was set to 540 rpm. However, the mechanical load generated at this speed was much smaller than that generated during the actual stem cutting, making it difficult to obtain accurate values. To solve this problem, the simulation was performed using various materials provided by the dynamic analysis software, and an acrylic rod was selected as the most suitable material. A torque sensor was then selected based on the simulation results using the acrylic rod and verified after being attached to the device.

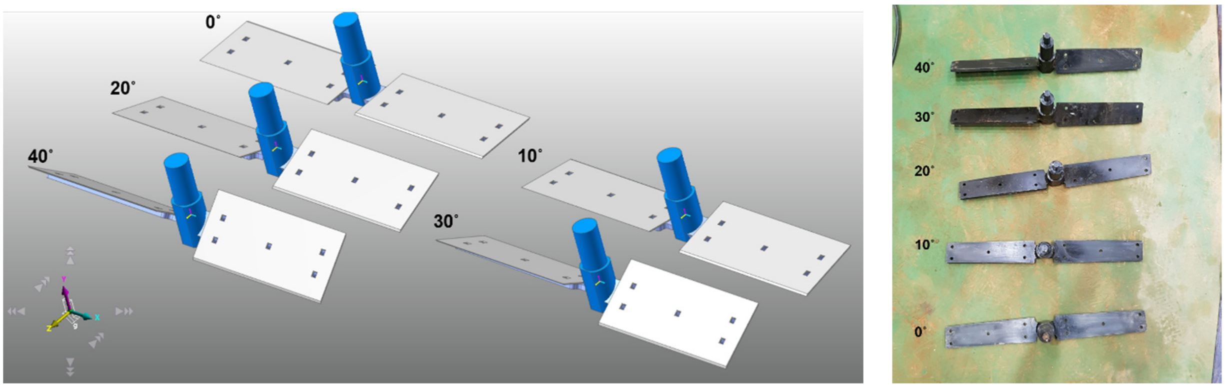

Figure 1. Three-dimensional drawings of stem cutter blades (**left**); manufactured stem cutter blades (**right**).

After verifying the torque sensor, the stem cutting test was conducted using the developed stem cutting test equipment. Tests were conducted to measure the vibration and noise generated by the blade rotating at a high speed and the load generated during stem cutting. The tests were performed using acrylic rods to simulate the mechanical properties of actual stems.

The stem cutting rate and shock exerted on the cutter blade were analyzed based on the data obtained from the stem cutting tests. The optimal installation angle was determined based on the analysis results. Finally, the function of the stem cutting machine was evaluated at different traveling speeds in the field.

Stem cutting experiments were conducted to determine the torque value exerted on the stem cutter blade. Because of the difficulty in directly measuring the torque value on the onion stem, an acrylic rod with a radius of 8 mm was used as a stem substitute. The properties of the stem cutter blade and acrylic rod, including the density, Young's modulus, and Poisson's ratio, were obtained and are summarized in Table 1.

Table 1. Material properties of steel and acrylic rod.

Material Property	Steel	Acrylic Rod
Density (kg/mm^3)	7.85×10^{-6}	1.18×10^{-6}
Young's modulus (N/mm^2)	200,000	3200
Poisson's ratio	0.285	0.394

2.2. Experiment for Stress Analysis with Stem Cutting Test Equipment

The stem cutting test equipment used to determine the optimal installation angle for the stem cutter blades is shown in Figure 2. The test equipment was 900 mm long, 900 mm wide, and 950 mm high. The equipment consisted of a shaft connected to a 700-W BLDC motor (TM10-D0721-24V, TMTECH-I, Bucheon-si, Republic of Korea) that rotated at a fixed speed of 540 rpm, as specified by the motor manufacturer and the damping ratio. The rotational speed was measured using a tachometer (HT-5500, ONO SOKKI Co., Ltd., Yokohama, Japan) to ensure accuracy before testing. The blades used in the experiment were 620 mm wide, 115 mm long, and weighed 5.1 kg. The blades were connected to the bottom shaft of the equipment. A torque sensor (SA_1KM, Corp. Cozy International, Ansan-si, Republic of Korea) was installed in the area where the shaft and blade were connected to measure the load generated during the test. The torque sensor was selected based on the simulation results using an acrylic rod as an onion stem substitute to measure the torque value exerted on the stem cutter blade.

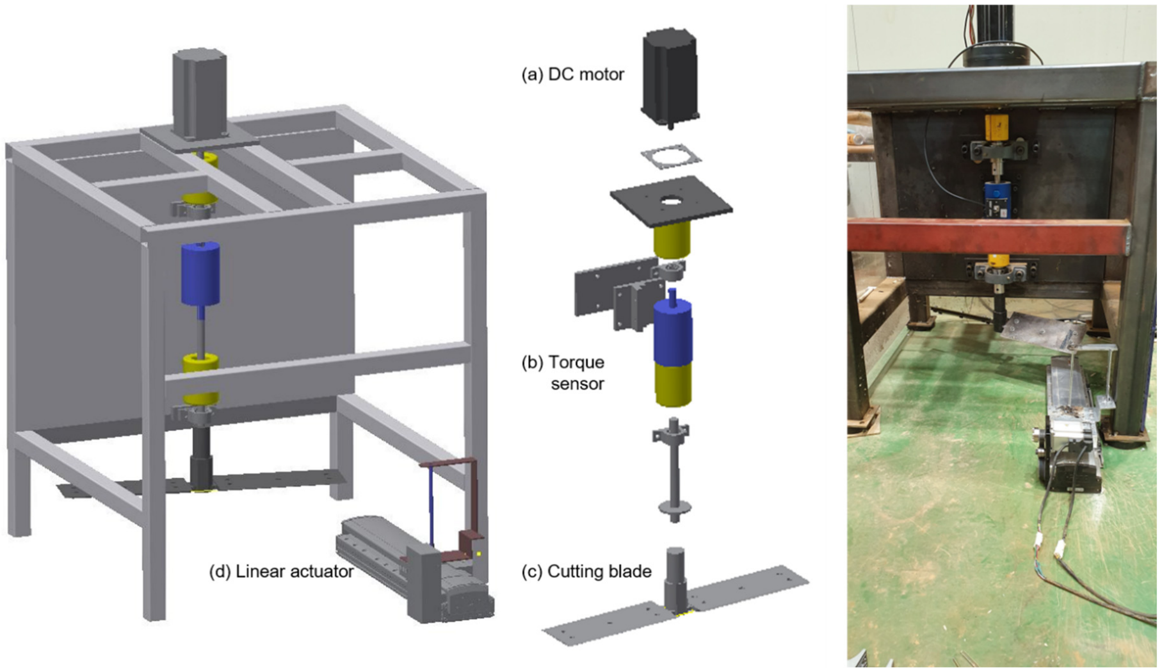

Figure 2. Three-dimensional design (**left**) and photograph (**right**) of stem cutting test equipment.

During the stem cutting test, the rotational speed, vibration, and sensor were stabilized. An acrylic rod with a radius of 8 mm was fixed to a linear actuator (PBA12548-300PLU+3SR, i-ROBO Co., Ltd., Gwangmyeong-si, Republic of Korea) and an AC motor (MSMD042G1S, Panasonic Corp., Japan) to be supplied in the direction of the stem cutter blade. A high-speed camera (HAS-D72, DITECT Corp., Tokyo, Japan) was used to verify if the acrylic rod was accurately supplied. The test was repeated 20 times to measure the load generated when the stems were cut at each installation angle.

Furthermore, the power consumption and wind velocity at each installation angle were measured using a motor meter (PM-2400A, AD Power, Bucheon-si, Republic of Korea) and portable anemometer (GT8907, Benetech, Kalisz, Poland) when the blade was rotated at 540 rpm. With a high-speed camera, the optimal installation angle for raising a stem was verified using leek samples with 60% and 80% moisture contents. Leek (*Allium porrum* L.) was chosen as a substitute for onions because it is the same Allium crop with a slightly different appearance but has a similar structure and physical properties to the stem part, which was used in this experiment.

2.3. Field Test of Tractor-Attachable Stem Cutting Machine

In 2017, the functionality of the tractor-attachable onion stem cutting machine was tested during an onion harvesting period in Chang-nyeong, Gyeongnam, Republic of Korea. The wind-blast-type onion stem cutting machine was developed by Bulls Co., Ltd., a joint research institute located in Sangju, Gyeongbuk. The machine had a total length of 1680 mm, width of 1970 mm, height of 1160 mm, horsepower of 50–60 HP, and a weight of 768 kg. The onion stem cutting blades were installed at an angle determined in the previous step. The functionality of the machine was compared and evaluated by performing stem cutting operations at traveling speeds of 0.4, 0.6, and 0.8 m/s. The stem cutting operation was aimed at leaving a remaining stem length of 10 cm after cutting.

3. Results and Discussion

3.1. Analysis of Stem Cutter Blade Installation Angle

In Figure 3a, the simulation shows the load generated when cutting the acrylic rod. High-speed camera shots showed the cutting process of the acrylic rod in the stem cutting test equipment (Figure 3b). The torque values measured when cutting the acrylic rod using the stem cutting test equipment and simulation analysis are listed in Table 2.

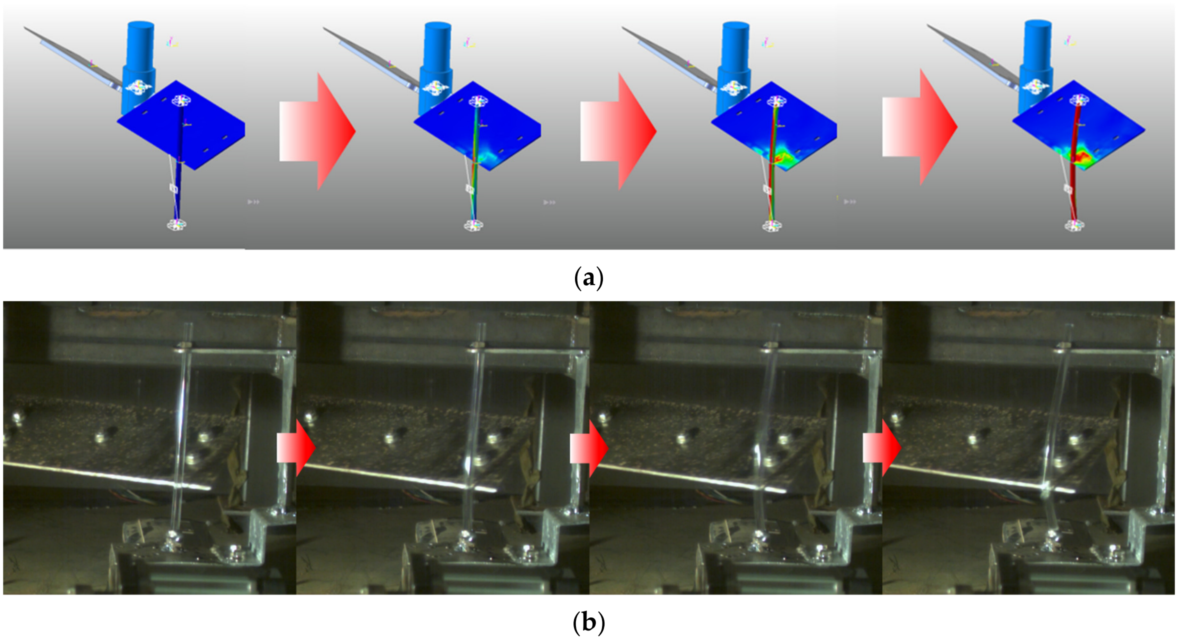

Figure 3. Change processes of shape when acrylic rods are cut (**a**) in simulation analysis and (**b**) using stem cutting test equipment.

Table 2. Results of the simulation analysis and stem cutting test equipment experiment for blade with different installation angles.

Installation Angle (°)	Torque Measured Value of Simulation Analysis (N·mm)	Torque Measured Value of Stem Cutting Test Equipment (N·mm)
0	930.92	1026.49
10	837.63	918.88
20	633.89	670.15
30	553.80	574.02
40	495.45	485.97

The results using the stem cutting test equipment were the average values of 20 replicate measurements at each installation angle. The torque values from the cutter blade in the simulation and stem cutting test equipment were shown at the installation angle of 0°; it was 930.92 N·mm in the simulation, whereas the highest value was 1026.49 N·mm using the stem cutting test equipment. As the angle increased, the torque decreased. The torque was 495.45 N·mm at the installation angle of 40° in the simulation, whereas the smallest torque was 485.97 N·mm using the stem cutting test equipment.

Consequently, we discovered that the optimal installation angle for creating the lowest load on the stem cutter blade was 40°. Compared with the torque at the installation angle of 0°, it was at a half-value level.

There were differences between the results obtained from the simulation and those from the stem cutting test equipment. However, the R^2 value between the two results was 0.99, indicating a significant correlation (Figure 4). Using this regression for analysis, we could estimate the torque value exerted on the cutting blades at different angles. Therefore, despite the difficulty to obtain accurate results from actual experiments, the simulation analysis can be helpful in understanding the trends.

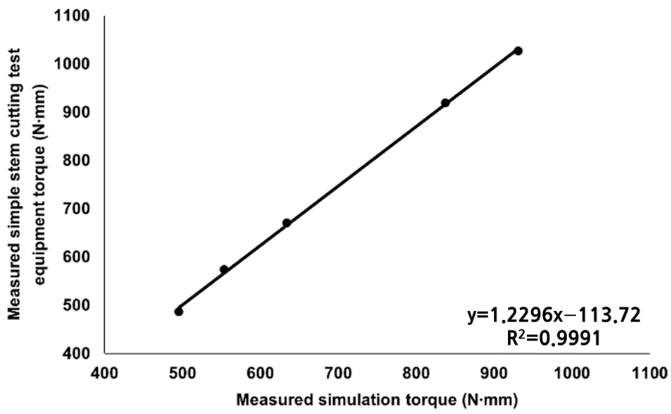

Figure 4. Correlation between simulation analysis and stem cutting test equipment results.

As the area where the rotating blade touches increases, more load is exerted on the motor. Therefore, with a larger installation angle, the area of the touched material increases, which can lead to damage due to the greater load exerted on the motor connected to the stem cutter blade. In addition, with a larger installation angle, the wind becomes stronger, consuming more power.

As shown in Table 3, the results of the motor power consumption test at different installation angles indicate that the current consumption increased by approximately four times as the installation angle increased from 0° to 40°. This implies that a larger load is exerted on the motor as the installation angle increases.

Table 3. Motor power consumption test at different installation angles.

Installation Angle (°)	Motor Power Consumption (Wh)
0	44.28
10	53.60
20	64.94
30	91.90
40	172.48

Finally, the velocity of the wind raising the stem at different installation angles was measured using a portable anemometer; the results are listed in Table 4. The wind velocity was measured as 0 m/s and 0.39 m/s at angles of 0 and 10 degrees, respectively, which was not suitable because there was no erection of the stem, as shown in Table 5. At an angle of 20 degrees, the wind velocity slightly increased to 0.44 m/s. However, as shown in Table 5, when the moisture content was 60%, it was possible to erect the stem, but the stem was only partially cut due to a slight lack of wind velocity. At 80%, it was not possible to cut because there was insufficient velocity to erect the stem. At angles of 30 and 40 degrees, the wind speed was measured as 0.75 m/s and 0.98 m/s, respectively, regardless of the water content, indicating that it was possible to cut the stem.

Table 4. Measured results of the velocity of wind raising the stem up at different installation angles.

Installation Angle (°)	Wind Velocity (m/s)
0	0
10	0.39
20	0.44
30	0.75
40	0.98

Table 5. Stem cutting at different moisture content and installation angles.

Moisture Content	0°	10°	20°	30°	40°
60%	not cut	not cut	partly cut	cut	cut
80%	not cut	not cut	not cut	cut	cut

During the harvesting season in Korea, over 70% of the onion stems are lodged [14] in onion farming fields.

However, the water content may differ depending on the weather conditions in the harvesting region or the onion variety. Considering these differences, it was found that the cutting blade should be installed at an angle greater than 30° to successfully cut the stem under any operational condition.

The stem cutter blade with an installation angle of 30° was deemed the most suitable for application in an actual stem cutting machine, considering the durability of the stem cutting machine and fuel consumption (Figure 5).

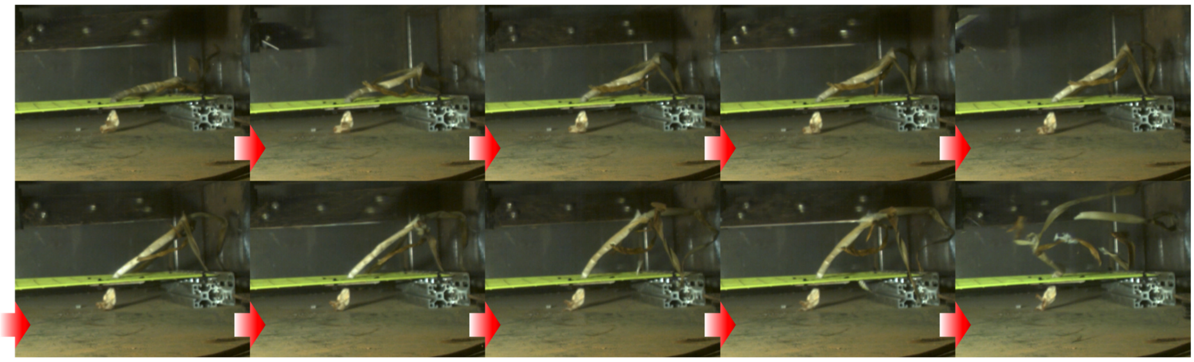

Figure 5. Raising of the stem at installation angle of 30° taken with a high-speed camera.

3.2. Validation with the Tractor-Attachable Wind-Blast-Type Onion Stem Cutting Machine

The results of the test on the tractor-attachable wind-blast-type onion stem cutting machine conducted in Chang-nyeong, Gyeong-nam, in 2017 are presented in Figure 6 and Table 6. After stem cutting, the remaining stem length was aimed to be 10 cm. The test was repeated thrice at a traveling speed of 0.4 m/s. The average remaining stem length was 9.98 cm, with a standard deviation of 4.72 cm and a stem cutting rate of 96.8%. At traveling speeds of 0.6 and 0.8 m/s, the average remaining stem lengths after cutting were 9.75 and 13.03 cm, respectively, and the standard deviations were 4.56 and 11.00 cm, respectively. The stem cut rates were 96.1 and 87.3%, respectively. The best results were obtained when the tractor-attachable wind-blast-type onion stem cutting machine was operated at a traveling speed of 0.4 m/s. However, when stem cutting was performed at a traveling speed of 0.6 m/s, it was possible to cut the stem with an extremely high probability of approximately 96%, and the remaining stem length was similar to the target of 10 cm. If stem height control is improved in the future, work time and labor can be likely reduced. After the test, the cut onion stems were placed in furrows on both sides of the ridge, as shown in the right picture of Figure 6. This was expected to reduce the load on the vinyl that covers the ridge during the removal process, minimize the possibility of tearing, and facilitate smoother work.

Using the stem cutter machine presented in this study, it was possible to cover an area of 10 hectare in just 1.5 h. This represents significant savings in time, labor, and cost compared to the 27.6 h [5] it would take to cover the same area using manual labor.

However, if the field conditions are uneven or the rotating speed of the rotating blade is not constant, the remaining stems of the onion may be uneven or the top of the onion may be damaged. Research on precise control and posture is necessary so that workers can set the desired stem height and make accurate cuts to prevent the future occurrence of damaged onions.

Figure 6. Onion stem cutting status by tractor-attachable wind-blast-type onion stem cutting machine (**left**) before works, (**middle**) working, (**right**) after works.

Table 6. Remaining stem length after stem cutting at each traveling speed.

Experiment			1st	2nd	3rd	Total
Tractor traveling speed (m/s)	0.4	Mean (cm)	10.81	8.65	10.48	9.98
		S. D. (cm)	4.16	3.95	5.68	4.72
		Cutting rate (%)	96.2	98.1	96.1	96.8
	0.6	Mean (cm)	10.98	9.25	9.01	9.75
		S. D. (cm)	4.67	4.29	4.55	4.56
		Cutting rate (%)	94.1	98.1	96.2	96.1
	0.8	Mean (cm)	16.27	11.22	11.56	13.03
		S. D. (cm)	14.70	8.94	7.37	11.00
		Cutting rate (%)	79.2	92.2	90.6	87.3

As mentioned in the introduction, many researchers and companies are trying to develop new products to improve the mechanization rate of field farming. However, commercialization requires high production costs and demand, and practical problems, such as crop diversification and difficulty in purchasing due to high prices, limit improvements in the mechanization rate [2]. Therefore, it is necessary to raise the level of the agricultural industry by preparing a system improvement and support plan at the governmental level.

4. Conclusions

In this study, we developed a tractor-attachable blast-type onion stem cutting machine and confirmed that the installation angle of 40° cuts onions with the smallest power using the optimal cutter blade installation. This was achieved using mechanism analysis programs and an actual simple equipment. The simulation analysis allowed us to save time and cost. In addition, the motor current consumption and wind speed were measured at different installation angles to determine the optimal installation angle, which was found to be 30°. We conducted a function test in the field after setting the actual stem cutting machine at the installation angle of 30° and found that the optimal traveling speed for cutting was 0.4 m/s, with a stem cutting rate of 96.8%.

The tractor-attachable blast-type onion stem cutting machine developed in this study is expected to provide a solution to the labor shortage issue in agricultural societies and decrease work time. However, owing to uneven field conditions, there were cases where the remaining stems of the onions were uneven or partially damaged, which can be detrimental to productivity on small farms, such as those in Korea. Therefore, future research should focus on developing a more sensitive device that can uniformly adjust the stem cutting height to maintain the remaining stem length at the same value as that confirmed in the field function test.

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Conflicts of Interest: The authors declare no conflict of interest.

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