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Physical and mechanical properties of hydroponic lettuce for automatic harvesting

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To design an automatic harvesting machine for hydroponic lettuce (Lactuca sativa L.), physical and mechanical properties of hydroponic lettuce were investigated and analyzed. Moisture content of stem, root and leaf, geometric characteristics, pulling force, and root cutting force were studied for harvesting hydroponic lettuce. The pulling force was examined by a tensile experiment, while the root cutting force was investigated by a shear experiment on the electronic universal testing machine. The moisture content of hydroponic lettuce was obtained by direct drying. Experiment data were processed using regression analysis and mathematical statistics method. A regression equation and the law of numerical distribution were obtained. The results showed that the geometric size of different hydroponic lettuce had little difference, and the distribution of physical parameters was concentrated. Moisture content was found statistically similar in stem and root (around 91%), while the highest moisture content was found in the leaf of 95.73%. The root cutting force decrease with the increase of cutting speed and decrease with the cutting position move downward. The minimum average root cutting force in the experiment was 1.41 N. The average pulling force was 13 N. This study provides adequate theoretical support for the design of the automatic harvesting machine of hydroponic lettuce.

1. Introduction

The population is increasing but the farmland is reducing in China. The supply of fresh vegetables has become an urgent problem [1]. Therefore, plant factories are being increasingly used to solve this problem [2]. Plant factory is an efficient agricultural system which can realize the annual continuous production of crops through environmental control in facilities. Hydroponic technology is a crop cultivation technique commonly used in plant factories. Hydroponic lettuce, a vegetable with a short growth cycle and high yield, has been widely cultivated in the plant factories [3]. Hydroponic lettuce is mainly planted on a planting board, and a deep flow technique, a hydroponic technique in which the plant roots grow in a deep and flowing nutrient layer, was used to cultivate lettuce. The hydroponic lettuce is pulled out from the planting board

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when it is mature, and the roots are cut as required. Then the lettuce is sold in packaging. At present, harvesting of hydroponic lettuce is carried out manually, with high labor costs and low efficiency [4,5]. Therefore, an automatic harvester that can process leafy vegetables is required.

Study of the physical and mechanical properties of vegetables plays a vital role in the development of automatic equipment [6]. Knowing the physical and mechanical properties of hydroponic lettuce will be useful for the development of harvesting machinery [7]. One of the basic and most important experiments in the study of mechanical properties of lettuce is the tensile experiment [8,9]. It can reflect some of the mechanical properties of the lettuce stem and whole lettuce. This paper will use similar vegetables as a reference to carry out research due to a lack of research on the mechanical properties of leafy vegetables. The researches on pulling force of similar vegetables were mainly focused on root crops such as radish (Raphanus sativus L.), carrot (Daucus carota L. var. sativa Hoffm.), and garlic (Allium sativum L.), etc. Several studies including Chen et al. [10], Li et al. [11] and, Fu et al. [12] have used the tensile experiment to obtain the pulling force of different varieties of radishes. They concluded that the maximum pulling force to harvest green radishes and red radishes were 90 N and 110 N, respectively. Xin et al. [13] also obtained that the main distribution range of garlic pulling force was from 24 to 27 N under the normal harvest condition. The cabbage (Brassica oleracea L.) harvester designed by Du et al. [14] can pull cabbages out of the soil with a success rate of 86.7%, but it can only be used in the field environment. At present, there are many studies on the pulling force of vegetables in the field, but fewer studies on the pulling force of hydroponic leafy vegetables in plant factories. Therefore, the pulling force of hydroponic leafy vegetables needs to be studied to develop automatic machinery in plant factories.

In addition to the tensile experiment, a shear experiment can be carried out to determine the root cutting force of hydroponic lettuce. Kanamitsu and Yamamoto [15] and Li et al. [16] have used shear experiments to obtain the root cutting force of cabbage. They found that the root cutting force can be affected by cutting position and cutting speed, while cutting position had a more significant impact on the root cutting force. Gao et al. [17] concluded the optimal parameters combination among cutting position, cutting mode, cutting speed, cutting angle, clamping position and clamping angle to harvest hydroponic lettuce through an orthogonal experiment. However, this study was only applicable to the way of removing the root harvest. Chen et al. [18] and Wu et al. [19] used orthogonal experiments to investigate the cutting forces of broccoli and rape, respectively. They both concluded that the cutting position was the key factor affecting the cutting force. Although the above-mentioned studies are not about lettuce, these studies provide support for the research of root cutting force of hydroponic lettuce. Presently, studies of hydroponic lettuce have generally been limited to the sensory attributes, general appearance, wilting, decay and physiological disorders conducted mostly during investigations on the packaging, processing and storage conditions [20–23], there are few studies on the root cutting force of hydroponic lettuce. However, the root cutting force is an important parameter in the design of the cutting device of hydroponic lettuce harvesting machinery. Therefore, the root cutting force should be investigated to develop the automatic harvester.

This study is aimed to investigate some of the physical and mechanical properties of hydroponic lettuce. It is carried out by means of using a tensile experiment, shear experiment, and moisture content experiment on multiple samples. The pulling force, root cutting force, geometric characteristics, and moisture content were obtained. The moisture content and pulling force are summarized and analyzed by mathematical statistics method. Meanwhile, the response surface method and variance analysis are used to analyze the change rule of root cutting force with different cutting positions and cutting speeds.

2. Materials and methods

2.1. Sample preparation

The hydroponic lettuces were randomly chosen from Yangling modern agricultural demonstration park in Shaanxi Province, China. A total of 100 samples were purchased for this study. The vegetables were ripe and defect-free. The experiments were conducted at the College of Mechanical and Electronic Engineering, Northwest A&F University, China. Because experimenting with all samples at once was impossible, the unused vegetables were grown in homemade Petri dishes.

2.2. Physical properties experiment

The design requirements of leaf vegetable harvesting machinery and the planting mode of hydroponic lettuce were referenced [24]. The physical parameters of hydroponic lettuce, such as crown diameter (CD), overlap length (OL), total height (TH), plant height (PH), total root length (TRL), main root length (MRL), stem diameter (SDi), maximum expansion diameter of the root (MED), total weight and net weight were selected as the evaluation indexes of the geometric characteristics of hydroponic lettuce [25,26]. The investigation was carried out using a digital vernier caliper (JDF03, SanLiang, Dongguan, China), a digital ruler (AH1740, AiHua, Hangzhou, China), and an electronic balance (PTT-A1000, BaoHeng, Shanghai, China) to measure the twelve parameters of hydroponic lettuce (Fig. 1). The CD is the maximum diameter of the projection of hydroponic lettuce in the horizontal plane under the natural growth state. The OL is the maximum value of the overlapping part of leaves with two adjacent lettuces in nature growth. The MRL is the distance between the planting board and the maximum root diameter of less than 30 mm (near the bottom of the root). The MED is the maximum diameter of the projection in the horizontal direction of the lettuce root after the root leaves nutrient solution. The net weight is the weight after cutting the root. The ruler was used to measure the PH, CD, and TRL while the digital vernier caliper was short for measuring. Thirty hydroponic lettuces were randomly selected from the 100 samples which were purchased to experiment with physical properties.

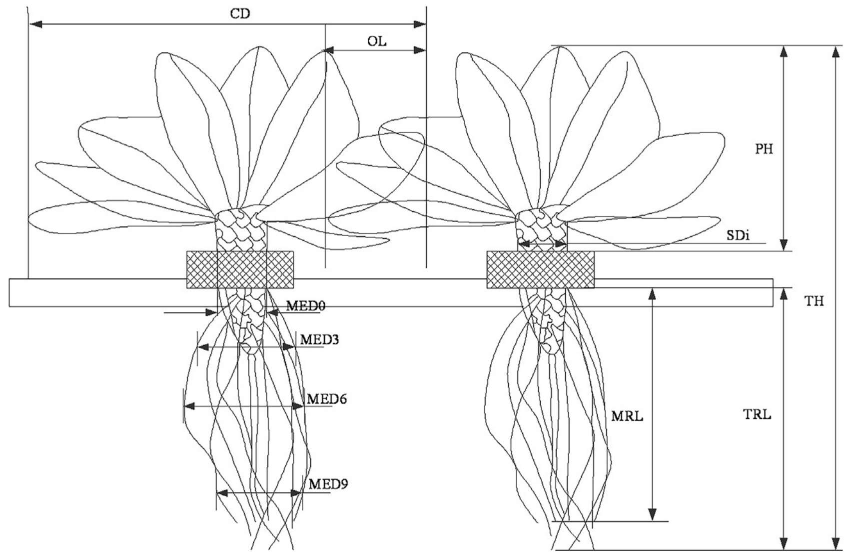

Fig. 1 – Physical characteristics of hydroponic lettuce. CD, crown diameter; OL, overlap length; TH, total height; PH, plant height; TRL, total root length; MRL, main root length; SDi, stem diameter; MED0, maximum expansion diameter of the root at 0 mm from planting board; MED3, maximum expansion diameter of the root at 30 mm from planting board; MED6, maximum expansion diameter of the root at 60 mm from planting board; MED9, maximum expansion diameter of the root at 90 mm from planting board.

2.3. *Moisture content experiment*

The direct drying method was used in this experiment to calculate the moisture content [27], according to the standard of GB / T 5009.3-2010 (Ministry of Health of the PRC 2010). The roots, stems, and leaves of hydroponic lettuce were divided into three groups because experimenting on the whole vegetable was impossible. The roots were cut into a segment with 30 mm, the stems were cut into thin slices with 2 mm, and the leaves were cut into strips with 5–10 mm. Five samples were selected randomly from each group for the experiment. The experiment was performed under room temperature by using a drying oven (DGG-9070AD, SENXIN, ShangHai, China), drying dish, and electronic balance. The weight of the drying dish and the total weight of drying dish with sample were measured, the weights were recorded as m_3 and m_1, respectively. Then the drying dish with sample was put into the drying oven at a temperature of 103℃±2℃. After 4 h, the drying dish with sample was taken out and weighed for the first time. The drying dish with sample should be weighed after cooling to room temperature, and tweezers were suggested to be used when moving the drying dish. After that, the weight of them was weighed every 1 h until the weight difference between two times was less than 2 mg. The final weight was recorded as m_2. Moisture content was calculated by Eq. (1).

$$X = \frac{m_1 - m_2}{m_1 - m_3} \times 100\% \quad (1)$$

where X is the Moisture content (%), m_1 is the total weight of drying dish and sample before drying (g), m_2 is the total weight of drying dish and sample after drying (g), and m_3 is the net weight of drying dish (g).

2.4. *Tensile experiment*

The maximum force to pull the hydroponic lettuce out of the planting board was called pulling force. The power consumption of the harvesting machinery and the design of the pulling device need a reference to the pulling force. A tension meter (SJ-50, SanLiang, DongGuan, China) and puller of hydroponic lettuce (Fig. 2) with a length 200 mm, a width 50 mm, a height 300 mm, and a U-shaped groove with a width of 25 mm was developed to determine the pulling force of hydroponic lettuce. The stem of hydroponic lettuce was placed in the U-shaped groove of the puller of hydroponic lettuce. The tension

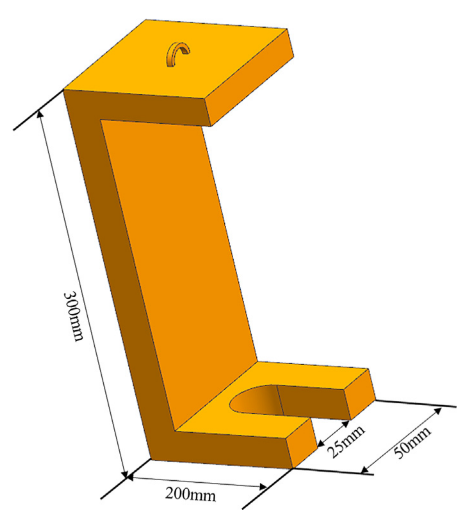

Fig. 2 – Puller of hydroponic lettuce.

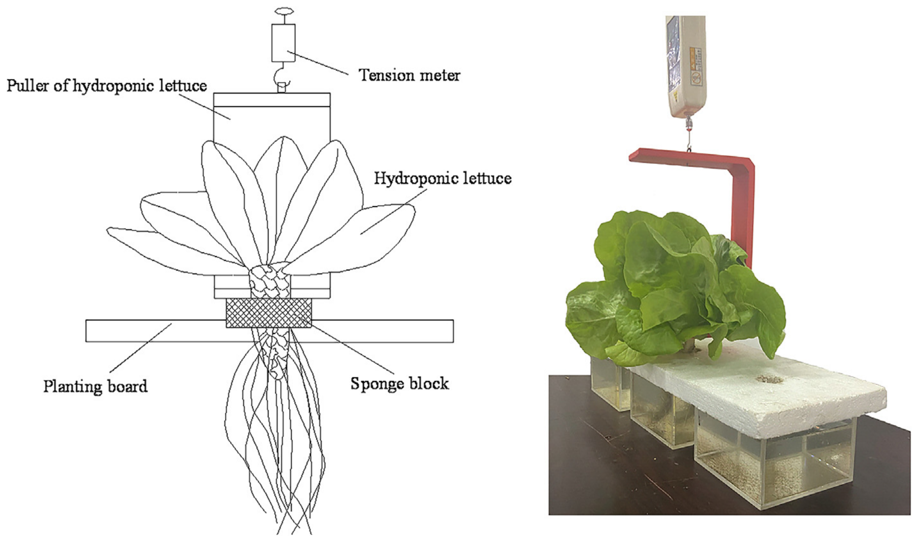

Fig. 3 – Method of pulling hydroponic lettuce from planting board.

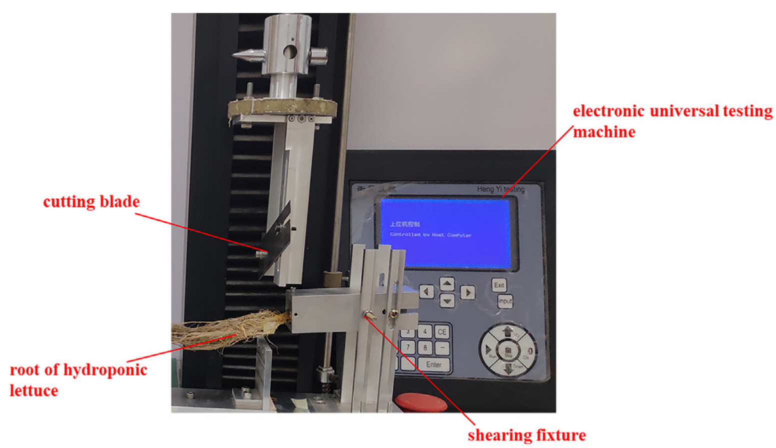

Fig. 4 – Experiment design of root cutting force.

meter was suggested to be placed vertically because the results from the tensile experiment were affected by the inclined angle of the tension meter. The tension meter was pull up slowly at a constant speed until the root of hydroponic lettuce was separated from the planting board. Then the maximum pulling force in this experiment was recorded. Thirty samples were randomly selected for the experiment. The sketch map and experimental field of the measurement method were shown in Fig. 3.

2.5. *Shear experiment*

Shear experiment was carried out to determine the necessary cutting force of a product with different cutting speeds and

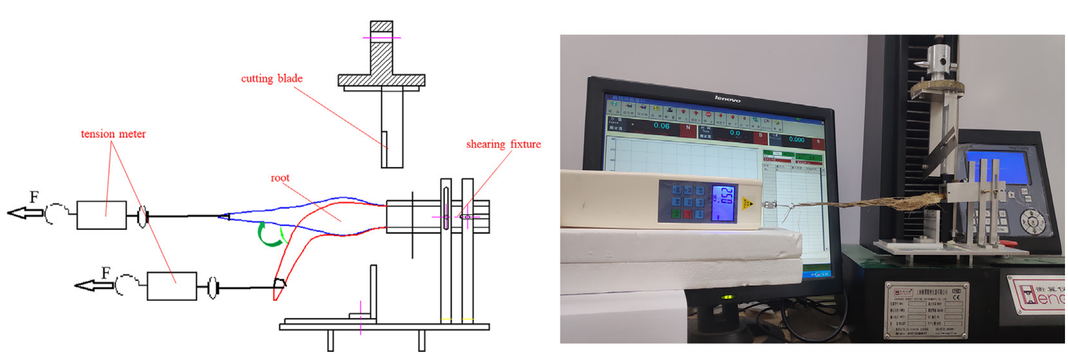

Fig. 5 – Experimental method of root cutting force.

cutting positions when shearing the hydroponic lettuce root. The cutting force plays an essential role in designing cutting devices of harvesting machinery [3]. The experiments were performed by using an electronic universal testing machine (HY-2030, HengYi, ShangHai, China) controlled by a computer, as shown in Fig. 4. The cutting angle was selected as 20° according to the actual cutting operation requirements. The root tip of hydroponic lettuce was connected with a tension meter. Then the root of hydroponic lettuce was slowly straightened. The tension value of tension meter is recorded as the specified tension when the root was just in a flat state, the sketch map and experimental field were shown in Fig. 5a and b, respectively. A single bevel blade with knife edge angle of 25° and made of carbon steel (65Mn) 0.5 mm thick was used in this study because of its strength and durability [28,29]. The hydroponic lettuce root could not be cut off when the cutting speed was less than 500 mm/min, but the cutting force tends to be stable with little change when the cutting speed was more than 900 mm/min. Therefore, the loading speeds of the cutting blade were selected as 500 mm/min, 600 mm/min, 700 mm/min, 800 mm/min, 900 mm/min, respectively. The average MRL of hydroponic lettuce is 95 mm, the cutting positions were selected as 0 mm, 30 mm, 60 mm, and 90 mm away from the planting board, respectively. These position corresponds to MED0, MED3, MED6, and MED9, as shown in Fig. 1. The hydroponic lettuce root was fixed on a shearing fixture and it was cut with different cutting speeds. The root was moved to the next position after completing shear experiment of one position. Every experiment was repeated 3 times in different cutting speeds and different cutting positions combination, then average results were compared statistically.

2.6. *Statistical analysis*

One-Way analysis of variance with Microsoft Office Excel 2016 software (Microsoft Corporation, USA) and Multi-Way analysis of variance with Design Expert 8.0 software (Stat-Ease Corporation, USA) were used for the analysis of variance of experimental data. In addition, a root cutting force model

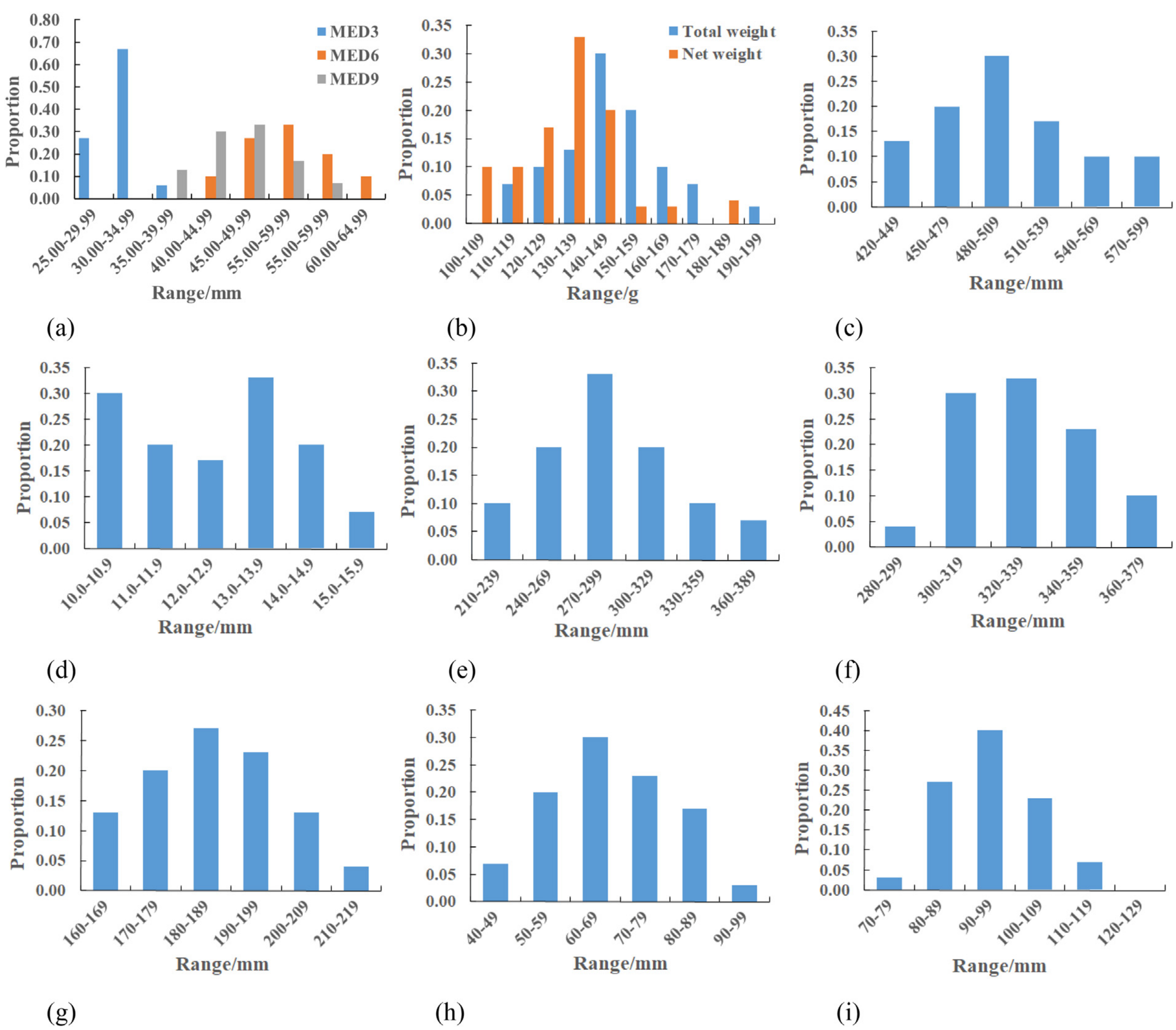

Fig. 6 – Physical parameters of hydroponic lettuce. (a) Maximum expansion diameter of the root (MED), (b) Weight, (c) Total height (TH), (d) Stem diameter (SDi), (e) Total root length (TRL), (f) Crown diameter (CD), (g) Plant height (PH), (h) Overlap length (OL), (i) Main root length (MRL).

Table 1 – Physical parameters of hydroponic lettuce.

	CD/mm	OL/mm	PH/mm	TH/mm	TRL/mm	MRL/mm	SDi/mm	MED3/mm	MED6/mm	MED9/mm	Total weight/g	Net weight/g
Maximum	378	94	212	578	374	114	15.48	35.74	63.21	57.06	196.36	179.67
Minimum	282	44	161	428	228	76	10.21	26.19	43.33	35.60	113.23	102.45
Average	331.6	67.9	185.8	495.57	290.9	95.17	13.10	31.29	52.14	46.30	148.44	133.14
SD	21.77	10.19	13.56	43.17	39.27	9.57	1.24	2.47	5.57	5.40	18.03	17.13
CV	0.07	0.15	0.07	0.09	0.13	0.10	0.09	0.08	0.11	0.12	0.12	0.13

SD, Standard Deviation; CV, Coefficient of Variation.

was built by a multivariate regressive method. The model was checked by an F-test (a way to check the stability of the model) in Design Expert 8.0 software [30]. The trend of root cutting force was predicted by the response surface method. The moisture content was determined by the direct drying method.

3. Results and discussion

3.1. *Physical parameters*

The main distribution range of CD of hydroponic lettuce was from 300 to 359 mm, which accounts for 87% of the total samples; the main distribution range of OL was from 50 to 89 mm, which accounts for 90% of the total samples; the main distribution range of pH was from 170 to 210 mm, which accounts for 83% of the total samples; the main distribution range of TH was from 450 to 569 mm, which accounts for 77% of the total samples; the main distribution range of TRL was from 240 to 359 mm, which accounts for 83% of the total samples; the main distribution range of MRL was from 80 to 109 mm, which accounts for 90% of the total samples; the main distribution range of SDi was from 11.0 to 14.9 mm, which accounts for 90% of the total samples; the main distribution range of MED3 was from 25.00 to 34.99 mm, which accounts for 94% of the total samples; the main distribution range of MED6 was from 45.00 to 59.99 mm, which accounts for 80% of the total samples; the main distribution range of MED9 was from 40.00 to 54.99 mm, which accounts for 83% of the total samples; the main distribution range of the total weight was from 130 to 179 g, which accounts for 80% of the total samples; the main distribution range of the net weight was from 120 to 169 g, which accounts for 77% of the total samples.

The histograms of these data obtained from physical properties experiments on hydroponic lettuce were shown in Fig. 6, and the geometric parameters of hydroponic lettuce were shown in Table 1. The longest MRL was 114 mm. Therefore, the depth of the nutrient tank should be greater than 114 mm to avoid the influence on the growth of lettuce. The varying of PH and CD were significant. The maximum values of PH (212 mm) and CD (378 mm) were suggested to be referenced when designing harvesting machinery to avoid the failure of harvesting. The MED can provide support for the design of the cutting devices. The MED with 63.21 mm is required to be acceptable when the cutting device is fully open. In addition, planting density and root extension of hydroponic lettuce will also affect the growth of the crop. Therefore, OL,

Table 2 – Moisture content of root, stem, and leaf of hydroponic lettuce.

	Root	Stem	Leaf
Maximum	94.35%	92.99%	97.04%
Minimum	89.04%	90.34%	94.53%
Average	91.85%	91.71%	95.73%
SD	0.02	0.01	0.01
CV	0.02	0.01	0.01

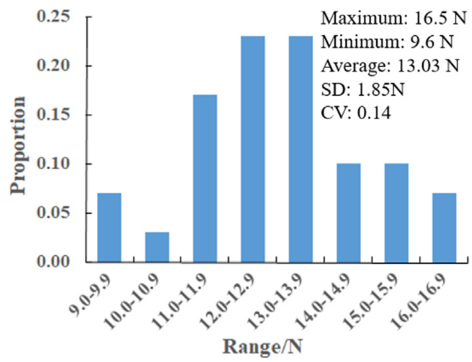

Fig. 7 – Pulling force of hydroponic lettuce.

TRL, and TH can be referenced when determining the plant spacing and cultivation mode. To select a planting board with suitable strength, the weight should be used as a reference standard. And the size of the planting hole in the planting board could be determined according to the maximum value of SDi (15.48 mm) of hydroponic lettuce. Meanwhile, it can be seen that the dispersion of physical parameters of hydroponic lettuce was small from the Coefficient of Variation (CV) less than 0.15. Therefore, harvesting machinery can be designed according to the main distribution range of physical parameters of hydroponic lettuce.

3.2. *Moisture content*

The moisture content of hydroponic lettuce was high, but the value of different parts were quite different. The moisture content of leaf was considerably higher than root and stem, the average moisture contents were 95.73%, 91.71%, 91.85% for leaf, stem, and root, respectively, as shown in Table 2. The CV of moisture content of stem, root, and leaf were less than the reference value of 0.15, which means that the data were reliable in this study. Xiang et al. [31] concluded that the moisture content of fresh-cut lettuce leaves was 96.8% during storage, which was similar to the result of this study. In addition, leafy vegetables with high moisture content were more likely to wither and rot [32]. Therefore, the automatic equipment should finish harvesting and packaging as soon as possible to avoid the impact on the quality of the product. Besides, although the moisture content of the stem was the lowest, it was easier to break because of its small toughness. Therefore, more protection should be given to this part in harvesting and packaging.

3.3. *Pulling force*

The maximum force and the minimum force of pulling hydroponic lettuce out of the planting board were 16.5 N and 9.6 N, respectively. The value of the average pulling force was 13.03 N with standard deviations (SD) of 1.85 N. The experimental data were within the normal range with CV was less than 0.15 specified in the evaluation data dispersion. The main distribution range of the pulling force of hydroponic lettuce was from 11.0 to 15.9 N, which accounts for 83% of the total samples, as shown in Fig. 7. Shandong Agricultural University Hu [33] reported the pulling force of spinach (Spinacia oleracea L.) was 14 N with the soil moisture content was 12.3% during harvest. The harvesting style of lettuce was comparable with spinach. Therefore, the harvesting machinery of spinach can be referred to when designing the harvesting machinery of lettuce. In addition, the planting board may be pulled up together with the hydroponic lettuce due to the

Table 3 – Experimental plan and result of root cutting force.

Num.	Factors		Root cutting force Y/N
	Cutting position X_1/mm	Cutting speed X_2/mm.min^{-1}	
01	0	500	27.43
02	0	600	25.95
03	0	700	21.44
04	0	800	20.01
05	0	900	18.55
06	30	500	22.99
07	30	600	19.58
08	30	700	16.42
09	30	800	15.60
10	30	900	13.84
11	60	500	9.46
12	60	600	7.72
13	60	700	4.99
14	60	800	3.17
15	60	900	2.77
16	90	500	5.86
17	90	600	4.73
18	90	700	3.44
19	90	800	1.88
20	90	900	1.41

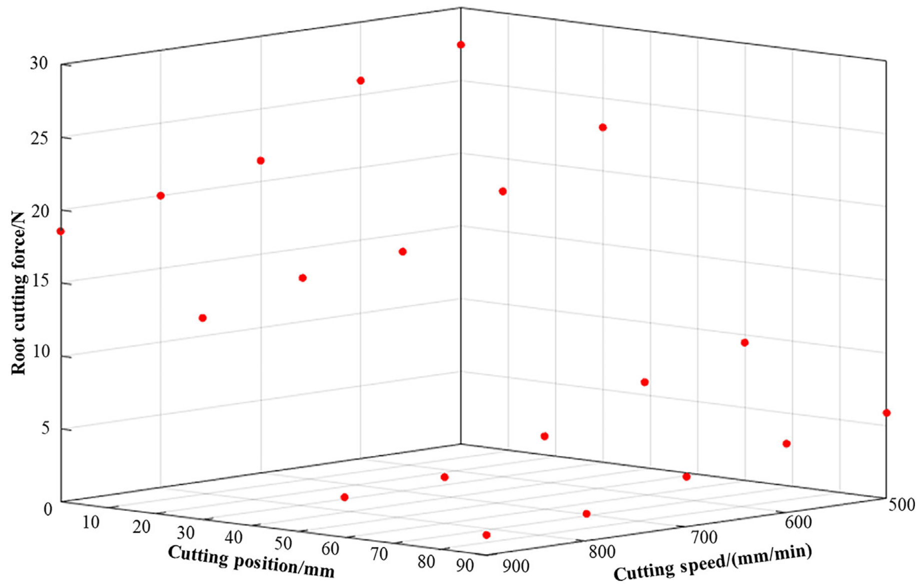

Fig. 8 – The root cutting force with different parameters combinations.

Table 4 – Variance analysis of regression equation for root cutting force.

Source	Sum of squares	Freedom	Mean square	F-value	P-value
Model	2.9	2	1.45	86.95	<0.0001
Cutting position	2.48	1	2.48	148.85	<0.0001
Cutting speed	0.42	1	0.42	25.04	0.0001
Residual	0.28	17	0.017	–	–

F value was the ratio of intergroup variation to intragroup variation, which indicates the significance of the item, and the larger the F, the stronger the significance. The *P*-value was the test level of the model. In this paper, values of *P* less than 0.05 indicate model terms were significant.

lightweight of the planting board. Therefore, the planting board was suggested to be fixed during the experiment and the actual harvest to avoid harvest failure.

3.4. *Root cutting force*

Thirty results were obtained through the shear experiment, as shown in Table 3. The scatter distribution was shown in Fig. 8. The maximum and minimum root cutting force were 27.43 N and 1.41 N, respectively. The maximum root cutting force appeared under the combination of cutting position of 0 mm and cutting speed of 500 mm/min. The minimum root cutting force appeared under the combination of cutting position of 90 mm and cutting speed of 900 mm/min. Generally, the root cutting force of hydroponic lettuce increased with the increase of cutting speed, and also increased with the distance from the planting board decreased.

The regression equation of root cutting force Y, cutting position X_1, and cutting speed X_2 was obtained, as shown in Eq. (2).

$$Y = 10 \wedge (0.94 - 0.47X1 - 0.2X2) \tag{2}$$

According to Eq. (2), the root cutting force Y was negatively correlated with the cutting position X_1 and the cutting speed X_2. The absolute value of the coefficient of cutting position X_1 was larger than that of cutting speed X_2. Therefore, the root cutting force Y was greatly affected by the cutting position X_1.

The variance analysis of the regression equation for the root cutting force was shown in Table 4. The *F*-value of the model of the regression equation was 86.95, and the *F*-value as a reference can be obtained from the standard F distribution table, which was 18.51 [34]. This result means that the model was significant (86.95 > 18.51). Meanwhile, the effect of cutting position and cutting speed on root cutting force were significant with *P*-value less than 0.05. In addition, the *F*-value of cutting position and cutting speed were 148.85 and 25.04, respectively. The influence of cutting position on the root cutting force was more significant than cutting speed (148.85 > 25.04).

The response surface method in Design Expert 8.0 was used to summarize the regulation of root cutting force [35]. The response surface figure between the cutting speed, cutting position, and root cutting force was shown in Fig. 9. It can be concluded: for the same cutting speed, the farther the cutting position from the planting board, the smaller the root cutting force, and for the same cutting position, the higher the cutting speed, the smaller the root cutting force. The minimum root cutting force was 1.41 N with the 900 mm/min of cutting speed and 90 mm of the distance between the cutting position and the planting board. Du et al. [36] and Li et al. [16] have reported the trend of root cutting force of cabbage with cutting position: root cutting force decreases with the cutting position close to the outermost

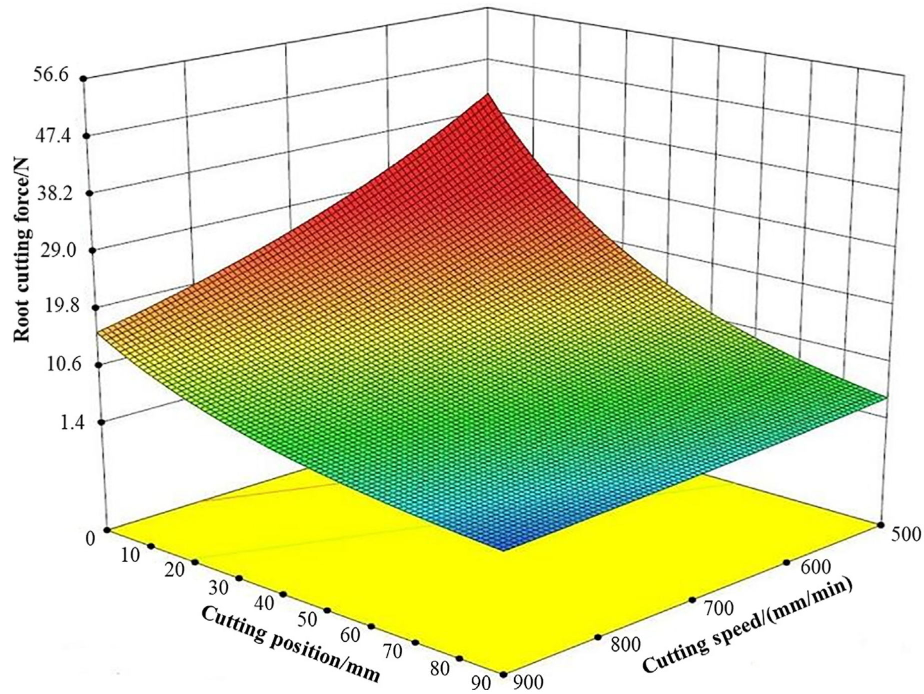

Fig. 9 – Response surface between cutting speed, cutting position and root cutting force.

leaf of cabbage, which consistent with the results of this study. Meanwhile, the trend of response surface was unanimous with the result of variance analysis.

3.5. *Application of lettuce characteristic research*

The value of lettuce characteristic research can be used in the harvesting stage and packaging stage of hydroponic lettuce processing. The ideal result used minimum force to finish harvesting without damaging the hydroponic lettuce. The average value of the moisture content of hydroponic lettuce was more than 90%. To ensure the quality of lettuce, the harvesting and packaging processing should be shortened as much as possible. The minimum value of the pulling force of 16.5 N can be applied effectively to ensure the hydroponic lettuce can be pulled out successfully. The planting board should be fixed to avoid pulling out together with hydroponic lettuce during harvest. The values of the root cutting force indicated the necessary forces to cut off the root with different cutting positions and different cutting speeds. The F-value of cutting position was 148.85, but the F-value of cutting speed was 25.04. The influence of cutting position on the root cutting force was more significant . To save energy, a further away from the planting board position should be selected to cut.

4. Conclusions

Some mechanical properties and physical properties of hydroponic lettuce were investigated. In this paper, the crown diameter (CD) of hydroponic lettuce samples ranged from 300 mm to 359 mm, and the mean value of plant height (PH) was 185.8 mm. The root cutting force and the pulling force of hydroponic lettuce in addition to the moisture content and the parameters of leaf, stem, and root were determined by the shear experiment and tensile experiment, respectively. Statistical comparisons indicated that the leaves have the highest moisture content, but the stems break most easily for short of toughness. The root cutting force of the hydroponic lettuce with different cutting speeds and cutting positions has also been analyzed. And the conclusion that the root cutting force was affected by the cutting position more significant was found out. Meanwhile, the pulling force of hydroponic lettuce was obtained by the tensile experiment, and the mean force was 13.03 N. The results of this study could be used in the design and optimization of mechanical harvesting and packaging equipment and for the development of new mechanical harvesting and packaging.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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