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Effect of Planting Distance on the Mechanical Harvesting of Hot Pepper

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Abstract: Hot peppers are well known for being spicy and also have a high nutrient content. Human resources have formerly been used to harvest hot peppers; however, a high level of musculoskeletal risk to the human workforce has been reported. Therefore, to reduce the risk to farmers and replace the human workforce, the mechanical harvesting of hot pepper and steps to improve the harvesting efficiency of farmers were conducted. To achieve this, the effect of planting distance on the mechanical harvesting of hot peppers was analyzed at three planting distances (30, 40, and 50 cm) with several cultivars. Subsequently, machine-harvested hot peppers were classified into five groups (marketable, damaged, lost, unharvested, and twigged hot pepper), depending on their postharvest status. The average weight ratio of each group was then calculated, after which statistical analyses were conducted. The effect of planting distance on mechanical harvesting was then analyzed by comparing the differences between each group's average weight ratio and the total weight of hot pepper, which was simultaneously harvested mechanically at each planting distance. Results showed that the average weight ratio of marketable, unharvested, and twigged hot pepper improved as the planting distance increased. However, no effect on the average weight ratio of damaged and lost hot pepper was observed. The highest yield of marketable hot pepper was found at a planting distance of 40 cm, and the average weight ratio to the whole was lower than at 50 cm of planting distance. Thus, the most suitable planting distance for mechanical harvesting was 40 cm.

Keywords: *Capsicum annuum* L.; hot pepper harvester; machinery harvest efficiency; planting distance

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1. Introduction

Hot pepper (*Capsicum annuum* L.) is among the most popular and demanded vegetables globally because of its intense flavor, attractive color, and high nutrient content [1,2]. Its nutrient content, such as L-ascorbic acid, soluble sugars, and carotenoids, are beneficial for human nutrition. Therefore, breeding methods have been studied previously to enhance its chemical quality [3–5].

Hot pepper is harvested manually, and it's cultivated area has been increasing globally [6]. It is well known that harvesting hot pepper requires long periods of manual labor; this results in the manifestation of many musculoskeletal problems among farmers. Studies have shown that farmers are exposed to higher risks of hazard when they manually harvest the crop. These includes musculoskeletal symptoms on their backs, knees, necks, and shoulders after daily work [7,8]. These long periods of field work also results in high labor costs, and continuous increase in base wage rates are annually [9]. Hence, the mechanical hot pepper harvester was developed and used for convenience to hazards faced by growers and replace human workforce. Unlike the manual harvesting process conducted several times, mechanical harvesting of hot pepper is undertaken only once. The quantity of mechanically harvested hot pepper, in addition to its harvesting efficiency, is better than handwork. Also, hot pepper cultivars should be highly resistant against anthrax which

occurs during late harvesting of the fruit. Field performance tests were conducted on double-opened helix-type harvesters by calculating their harvesting efficiency, successful harvesting rates, pepper with twig rates, pepper left on plant rates, and ground fall loss rates at different rotational speeds of the helix. As reported, the harvesting efficiency increased with an increase in the speed of the helix; however, pepper with twigs and damage rates also increased. Thus, successfully harvesting rates require improvements in all rotational speeds of the helix [10].

Furthermore, comparisons of mechanical harvesting performance among five harvest mechanisms, including comparisons of harvest efficiency among four hot pepper cultivars, were conducted. From the study, all cultivars' harvest efficiencies were <70%, and the double-open helix mechanism had the best machine-harvest performance among those five, with a harvest efficiency of 88.3%. However, this mechanism also had the highest ratio of the whole to damaged fruit, and the low yield of marketable hot pepper was unsatisfactory [11]. Likewise, the mechanical harvest efficiency of six new Mexican hot pepper cultivars showed an efficiency below 60%, and the average yield of the six cultivars under study was 27.3 ton/ha. Nevertheless, considering that the yield of pepper in studies conducted in the United States of America, and Europe was 31.8 and 32.02 ton/ha, respectively, in 2019, his yield value desperately required improvement for sustainability. Another factor for yield differences among cultivars that were also analyzed was the architecture of the plant [6,12]. Moreover, a study reported that commercialized harvesters had a severe problem with the low harvest efficiency of commercial hot pepper that reduced the yield of these hot peppers. Thus, the hot pepper harvester needed improvement by reducing its damage to the crop and minimizing the ground-fallen peppers [13].

A previous study indicated that mechanical harvest efficiency was related to plant structure [14], proposing that the growth of the pepper plant is related to the planting distance. Therefore, planting distance affected the growth of pepper plants, including yield, number per plant, and weight of plant [15,16]. Furthermore, the growth of the pepper plant, such as plant height, fruit diameter, fruit thickness, and fruit length, increased with distance [17,18]. The yield of hot peppers per plant and stem girth also increased with distance [19–21]. These results, wherein planting distance influenced the number of fruits and weight of fruits per plant were confirmed in other plants, such as cocoyam, mango, onion, rice, and tomato [22–26].

Based on these findings, it was evident that the planting distances of hot pepper plants were highly related to the quantity of the pepper obtained at harvest and affected mechanical harvesting efficiency. However, planting distance was used at a variety of levels: 35 cm in Canada [27], 38–45 cm in the United Kingdom [28], 30–45 cm in America [29,30], 30 cm in Brazil [31], and 30–40 cm in the Republic of Korea [32]. Based on the total yield of hot peppers per plant and marketable fruit yield per plant, a previous study indicated that a low planting density resulted in a high total yield of hot pepper [33–35]. There are suggested planting distance for manual work in each country, but there is no recommended planting distance for mechanical harvesting to the best of our knowledge. Consequently, a comparison of different planting distances to improve mechanical harvesting efficiency was conducted in this study.

2. Materials and Methods

2.1. Hot Pepper Harvester

Hot pepper harvesters (CH301, TYM CO., LTD., Daegu, Republic of Korea) comprised of three main components: threshing, transporting, and loading bay. The threshing component was placed in front of the machine, where the rotating double-helix system threshes the whole plant and pulls out the fruit. Then, the harvested fruit is transported to the loading bay, after which a motor-created airflow was used to separate leaves. The specifications of the hot pepper harvesting machine used in this study are presented in Figure 1 and Table 1 [36].

Figure 1. Hot pepper harvester used for the field test.

Table 1. Specifications of the hot pepper harvester.

Hot Pepper Harvester	Specifications
Model	CH301 (TYM CO., LTD./Republic of Korea)
Company/country	TYM CO., LTD./Republic of Korea
Length/width/height (mm)	4380/1810/1800
Ground clearance (mm)	600
Engine power (kW)	20.1
Revolution speed of helix (RPM)	700
Weight (kg)	2065
Work speed (km/h)	1.6
Maximum capacity of loading bay (kg)	200
Diameter of the helix (mm)	100
Length of helix (mm)	1700

2.2. Cultivars

Three hot pepper cultivars were selected: AR Legend (Pepper & Breeding Institute, Gimje, Republic of Korea), Maeuntan (Syngenta Korea, Daegu, Republic of Korea), and Jeockyoung (Rural Development Administration, Jinju, Republic of Korea).

2.3. Planting Distance

Hot peppers were harvested using the double-helix harvester with a threshing component, where the whole pepper plant goes through the gap between the double-helix. Consequently, controlling the planting distance is proposed to decrease the impact between pepper plants, thereby earning enough time for the harvester to thresh the whole pepper plant before a new inflow.

Therefore, to obtain a low planting density, a narrow planting distance was required. For planting distance, 30–50 cm is used globally. Thus, in this study, three levels of planting distances were selected for the mechanical harvesting experiment (Figure 2).

(**a**) (**b**) (**c**)

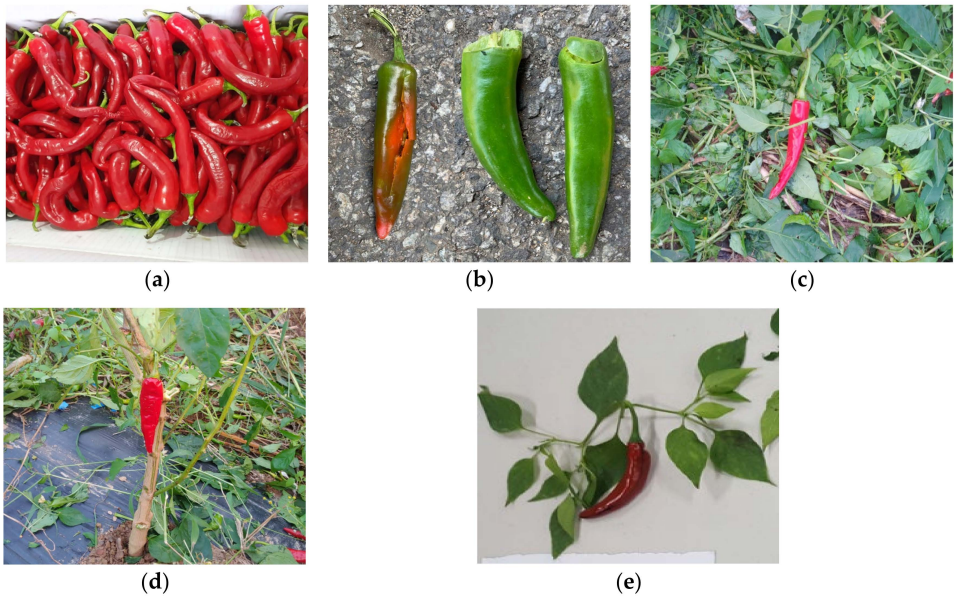
Figure 2. Three levels of planting distance selected for harvesting experiment (**a**) 30 cm planting distance, (**b**) 40 cm planting distance, (**c**) 50 cm planting distance.

2.4. Field Conditions

The experiment was conducted at the upland-field machinery research center at Gunwi-gu, Gyeongsangbuk-do, Republic of Korea (latitude 36°06′55.1″-N, longitude 128°38′28.1″-E). The field area was 1487 $m^{2,}$ and the soil was clay loam with a pH of 6.2. The experimental region had an average annual air temperature between 30.2 °C and 19.2 °C, and a 460 mm average annual rainfall during summer. The distance between rows was 130 cm, with three rows in each cultivar, and the length of each row was 90 m. All cultivars were sown on 3 March 2020, raised for 75 days, and transplanted on 18 May 2020. The pepper plant reached 80 cm in height in all cultivars.

2.5. Mechanical Harvest

The mechanical harvest was conducted at 10 m for each planting distance. The constant forward speed of the harvester was 1.6 km/h, and the rotational speed of the helix was 700 rpm. After 10 m mechanical harvesting, harvested peppers were manually classified into five groups depending on their status, and fresh weight was used for measurement (Figure 3). The groups included marketable, damaged, lost, unharvested, and twigged hot peppers. Marketable hot pepper was defined as well-harvested pepper, which is whole and safely transported into the loading bay; damaged hot pepper was defined as that which was ripped and chopped; lost hot pepper was defined as ground-fallen peppers during mechanical harvesting; unharvested hot pepper was the fruit left after mechanical harvesting; and twigged hot pepper was defined as those peppers still having twigs and leaves attached postharvest.



(**a**) (**b**) (**c**)

(**d**) (**e**)

Figure 3. Image of classified machinery-based harvested peppers (**a**) marketable hot pepper, (**b**) damaged hot pepper, (**c**) lost hot pepper, (**d**) unharvested hot pepper, and (**e**) twigged hot pepper.

Following this, each group was weighed using an electric scale (PAG4102, OHAUS, Parsippany, NJ, USA). The mechanically harvested hot pepper in the loading bay consisted of five groups of hot pepper. For analysis of the percentage of each group in the loading bay after 10 m of harvesting, the weight ratio of the whole weight of mechanically harvested pepper was calculated using Equation (1) below with the parameters shown in Table 2.

$$R_n = \frac{S_n\ (kg)}{\sum_{n=1}^{5} S_n\ (kg)} \times 100\ (\%) \quad (1)$$

Table 2. Symbols and definitions for equation one.

Symbols	Definitions	Symbols	Definitions
R_1	The weight ratio of marketable hot pepper	S_1	Weight of marketable hot pepper
R_2	The weight ratio of damaged hot pepper	S_2	Weight of damaged hot pepper
R_3	The weight ratio of lost hot pepper	S_3	Weight of lost hot pepper
R_4	The weight ratio of unharvested hot pepper	S_4	Weight of unharvested hot pepper
R_5	The weight ratio of twigged hot pepper	S_5	Weight of twigged hot pepper

2.6. Statistical Analysis

Statistical analysis was conducted using SPSS (IBM SPSS Statistics 26, IBM, Armonk, NY, USA) at a 5% significance level. Results are presented for each group regarding the mean weight ratio, conducted nine times during mechanical harvesting experiments. Furthermore, the difference in weight ratios between planting distances was elaborated using one-way analysis of variance (ANOVA) with Duncan's test. Pearson's correlation test was conducted to elaborate on the relationship between the planting distance and the weight ratio of each classified group. Furthermore, multiple ways ANOVA was conducted to analyze the effect of planting distance on the variables and to compare the three cultivars statistically.

3. Results

3.1. Marketable Hot Pepper

Mechanical harvesting efficiency at different planting distances was evaluated using the weighted ratio of marketable, damaged, lost, unharvested, and twigged hot peppers. Table 3 presents the mean statistical analysis of the weight ratio obtained from marketable harvested hot peppers in all cultivars. Comparing the planting distances, the average weight ratios were 71.1 ± 4.0% (SD), 77.1 ± 3.5% (SD), and 81.5 ± 2.2% (SD) for AR legend; 74.3 ± 3.0% (SD), 80.0 ± 1.4% (SD), and 82.1 ± 1.9% (SD) for Maeuntan; and 71.0 ± 1.5% (SD), 74.5 ± 2.1% (SD), and 81.1 ± 2.2% (SD) for Jeockyoung. Results showed that the average weight ratio of marketable hot pepper increased with planting distance. Moreover, the highest weight ratio of marketable hot pepper was indicated at a planting distance of 50 cm for all cultivars. Furthermore, results of the ANOVA on the effects of planting distance and cultivar on the weight ratio of marketable hot pepper showed a significantly different effect as all p-values were <0.05. However, there was no interaction effect between planting distance and cultivar as the p-value was >0.05.

Furthermore, previous studies have reported that yield per plant was significantly influenced by planting distance. The yield per plant was also increased with an increase in planting distances [19,33,35]. However, further planting distances caused a leak in pepper yield because increased planting distances meant fewer plants per unit area of hot pepper fields. Therefore, the highest weight of marketable hot pepper was obtained at a 40 cm planting distance (Table 3), with 7.0 ± 0.2 kg (SD) for AR Legend, 9.5 ± 0.7 kg (SD) for Maeuntan, and 6.2 ± 0.5 kg (SD) for Jeockyoung obtained for all cultivars. Hence, we propose that the most suitable planting distance for mechanical harvesting of hot pepper is 40 cm.

Table 3. Statistical analysis results on marketable hot pepper.

Cultivar	PD (cm)	M ± SD (%)	Weight (kg)	PCC	F-Value	*p*-Value
AR Legend	30	71.1 ± 4.0 a [(1)]	5.9 ± 0.25			
	40	77.1 ± 3.5 b	7.0 ± 0.2	0.780 **	11.928	0.001
	50	81.5 ± 2.2 b	6.3 ± 0.1			
Maeuntan	30	74.3 ± 3.0 a	8.0 ± 0.3			
	40	80.0 ± 1.4 b	9.5 ± 0.7	0.802 **	16.331	0.000
	50	82.1 ± 1.9 b	8.2 ± 0.4			
Jeockyoung	30	71.0 ± 1.5 a	5.3 ± 0.4			
	40	74.5 ± 2.1 b	6.2 ± 0.5	0.889 **	33.191	0.000
	50	81.1 ± 2.2 c	5.1 ± 0.3			

Group	Source	DF	ANOVA SS	Mean Square	F-Value	*p*-Value
Marketable hot pepper	PD	2	804.111	402.056	49.478	0.000 **
	Cultivar	2	100.778	50.389	6.201	0.004 **
	PD*Cultivar	4	35.444	8.861	1.090	0.373
	Error	45	365.667	8.126		
	Total	53	1306.000			

PD: Planting Distance; M: Mean; SD: Standard Deviation; PCC: Pearson's Correlation Coefficient; SS: Sum of Squares. [(1)]: Mean separation within columns by Duncan's Multiple Range test at $p = 0.05$. ** $p < 0.01$.

3.2. Damaged Hot Pepper

The physical quality of hot pepper, which was pre-harvested manually, and hot pepper, which was post-mechanically harvested are shown in Figure 4. This method of quality assessment was adopted because it was difficult to carry out the standard wet chemistry methods. These wet chemistry methods are also destructive and time-consuming. The assessment showed that the physical quality of the two hot peppers (Figure 4a,b) was defined with no chop or rip on their pericarp. The statistical analysis of the average weight ratio of damaged hot pepper is shown in Table 4. Comparing between the planting distances, the average weight ratios were 4.2 ± 1.4% (SD), 2.5 ± 0.7% (SD), and 2.2 ± 0.3% (SD) for AR legend; 3.8 ± 1.6% (SD), 3.7 ± 0.9% (SD), and 3.5 ± 0.9% (SD) for Maeuntan; and 4.8 ± 1.8% (SD), 4.2 ± 1.0% (SD), and 3.0 ± 1.5% (SD) for Jeockyoung. The average weight ratio of damaged hot pepper was only related to the planting distance; no significantly different interaction effect was found between planting distance and cultivar. Furthermore, most damaged hot peppers were recorded during transportation to the loading bay; thus, we suspect that too much force was applied to the hot pepper, resulting in the peppers being chopped and ripped out. Compared with a previous study on mechanical harvesting experiments, the damaged ratio observed in this study was much lower (8.37%) because the broader and blockier structure of the hot pepper ridges, characterized by the different planting distances, was more acceptable in managing the mechanical damage [10]. Furthermore, additional studies with fruit damage measurement in each harvester unit are required and would be done in the future.

(**a**) (**b**)

Figure 4. Physical quality of hot pepper (**a**) manually pre-harvested and (**b**) post-mechanically harvested.

Table 4. Statistical analysis results on damaged hot pepper.

Cultivar	PD (cm)	M ± SD (%)	Weight (kg)	PCC	F-Value	*p*-Value
AR Legend	30	4.2 ± 1.4 b [(1)]	0.4 ± 0.2	−0.623 **	6.019	0.012
	40	2.5 ± 0.7 a	0.2 ± 0.1			
	50	2.2 ± 0.3 a	0.2 ± 0.1			
Maeuntan	30	3.8 ± 1.6 a	0.4 ± 0.2	−0.109	0.090	0.914
	40	3.7 ± 0.9 a	0.4 ± 0.1			
	50	3.5 ± 0.9 a	0.3 ± 0.1			
Jeockyoung	30	4.8 ± 1.8 a	0.2 ± 0.1	−0.440	1.860	0.190
	40	4.2 ± 1.0 a	0.4 ± 0.1			
	50	3.0 ± 1.5 a	0.2 ± 0.1			
Group	**Source**	**DF**	**ANOVA SS**	**Mean Square**	**F-Value**	***p*-Value**
Damaged hot pepper	PD	2	17.593	8.796	4.576	0.016 **
	Cultivar	2	10.481	5.241	2.726	0.076
	PD*Cultivar	4	6.852	1.713	0.891	0.477
	Error	45	86.500	1.922		
	Total	53	121.426			

PD: Planting Distance; M: Mean; SD: Standard Deviation; PCC: Pearson's Correlation Coefficient; SS: Sum of Squares. [(1)]: Mean separation within columns by Duncan's Multiple Range test at $p = 0.05$. **: $p < 0.01$.

3.3. Lost Hot Pepper

The statistical analysis of the average weight ratio of lost hot pepper are shown in Table 5. Comparing planting distances, the average weight ratios were 4.2 ± 1.3% (SD), 3.8 ± 1.3% (SD), and 4.8 ± 2.6% (SD) for AR legend; 3.0 ± 1.0% (SD), 2.8 ± 0.9% (SD), and 5.1 ± 1.2% (SD) for Maeuntan; and 4.0 ± 1.0% (SD), 4.1 ± 2.3% (SD), and 2.1 ± 1.3% (SD) for Jeockyoung. Results also showed that the average weight ratios of lost hot pepper cultivars did not relate to the planting distance or cultivar; therefore, no significantly different effect was observed. The result of two-way ANOVA indicated that there was an interaction effect between planting distance and cultivar. Therefore, the weight ratio of lost hot pepper was significantly different when planting distance and cultivar were considered. Most lost hot peppers were observed during transportation and probably caused by airflow, which was created in the harvester for separating the fruits from the leaves.

3.4. Unharvested Hot Pepper

Table 6 presents the statistical analysis results of average weight ratios of unharvested hot peppers in all cultivars. Comparing the planting distances, the average weight ratio was 10.0 ± 1.2% (SD), 8.8 ± 2.6% (SD), and 5.5 ± 1.3% (SD) for AR Legend; 9.3 ± 2.4% (SD), 7.5 ± 1.9% (SD), and 5.0 ± 1.0% (SD) for Maeuntan; and 10.5 ± 0.5% (SD), 8.6 ± 0.7% (SD), and 7.5 ± 0.7% (SD) for Jeockyoung. From the results, the weight ratio of unharvested hot pepper decreased with the planting distance and cultivar. The lowest weight ratio of unharvested hot pepper was at a planting distance of 50 cm for all cultivars. Nevertheless, results of the ANOVA regarding the effect of planting distance on the average weight ratio of unharvested hot pepper showed a significantly different effect as all *p*-values were <0.05, and but no interaction effect between planting distance and cultivar was found as the *p*-value was >0.05.

3.5. Twigged Hot Pepper

Statistical analysis results of the average weight ratio of twigged hot pepper are shown in Table 7. Comparing the planting distances, the average weight ratios were 10.5 ± 1.3% (SD), 7.5 ± 1.2% (SD), and 6.1 ± 2.6% (SD) for AR legend; 9.8 ± 0.6% (SD), 5.3 ± 0.4% (SD), and 4.1 ± 0.9% (SD) for Maeuntan, and 10.3 ± 1.9% (SD), 8.3 ± 1.8% (SD), and 6.1 ± 0.9% (SD) for Jeockyoung. As shown, the weighed ratios of twigged hot pepper cultivars decreased with the planting distance, and the lowest weight ratio of twigged hot peppers was at a planting distance of 50 cm for all cultivars. Moreover, the results of the ANOVA on the effect of planting distance and cultivar on average weight ratios

of twigged hot peppers showed significantly different effects as all p-values were <0.05, but no interaction effect between planting distance and cultivar was found. Likewise, in a previous study, the whole to twigged ratios of AR Legend and Jeockyoung were 44.3% and 23.1%, respectively, respectively [9].

Table 5. Statistical analysis results for lost hot pepper.

Cultivar	PD (cm)	M ± SD (%)	Weight (kg)	PCC	F-Value	*p*-Value
AR Legend	30	4.3 ± 1.3 a (1)	0.4 ± 0.1			
	40	3.8 ± 1.3 a	0.4 ± 0.1	0.105	0.346	0.713
	50	4.8 ± 2.6 a	0.2 ± 0.1			
Maeuntan	30	3.0 ± 1.0 a	0.3 ± 0.1			
	40	2.8 ± 0.9 a	0.4 ± 0.1	0.593 **	7.754	0.005
	50	5.1 ± 1.2 b	0.6 ± 0.1			
Jeockyoung	30	4.0 ± 1.0 a	0.2 ± 0.1			
	40	4.1 ± 2.3 a	0.3 ± 0.1	−0.396	2.232	0.142
	50	2.1 ± 1.3 a	0.2 ± 0.1			
Group	**Source**	**DF**	**ANOVA SS**	**Mean Square**	**F-Value**	***p*-Value**
Lost hot pepper	PD	2	1.815	0.907	0.304	0.739
	Cultivar	2	7.704	3.852	1.290	0.285
	PD*Cultivar	4	36.296	9.074	3.040	0.027 **
	Error	45	134.333	2.985		
	Total	53	180.148			

PD: Planting Distance; M: Mean; SD: Standard Deviation; PCC: Pearson's Correlation Coefficient; SS: Sum of Squares. (1): Mean separation within columns by Duncan's Multiple Range test at $p = 0.05$. ** $p < 0.01$.

Table 6. Statistical analysis results on unharvested hot pepper.

Cultivar	PD (cm)	M ± SD (%)	Weight (kg)	PCC	F-Value	*p*-Value
AR Legend	30	10.0 ± 1.2 b (1)	0.9 ± 0.1			
	40	8.8 ± 2.6 b	1.1 ± 0.1	−0.690 **	7.874	0.005
	50	5.5 ± 1.3 a	0.5 ± 0.1			
Maeuntan	30	9.3 ± 2.4 b	1.3 ± 0.2			
	40	7.5 ± 1.9 ab	1.1 ± 0.2	−0.681 **	6.568	0.009
	50	5.0 ± 1.0 a	0.5 ± 0.1			
Jeockyoung	30	10.5 ± 0.5 c	0.8 ± 0.1			
	40	8.6 ± 0.7 b	0.7 ± 0.1	−0.869 **	24.700	0.000
	50	7.5 ± 0.7 a	0.5 ± 0.1			
Group	**Source**	**DF**	**ANOVA SS**	**Mean Square**	**F-Value**	***p*-Value**
Unharvested hot pepper	PD	2	141.593	70.796	23.512	0.000 **
	Cultivar	2	23.370	11.685	3.881	0.028 **
	PD*Cultivar	4	8.074	2.019	0.670	0.616
	Error	45	135.500	3.011		
	Total	53	308.537			

PD: Planting Distance; M: Mean; SD: Standard Deviation; PCC: Pearson's Correlation Coefficient; SS: Sum of Squares. (1): Mean separation within columns by Duncan's Multiple Range test at $p = 0.05$. **: $p < 0.01$.

3.6. Twigged Hot Pepper

Statistical analysis results of the average weight ratio of twigged hot pepper are shown in Table 7. Comparing the planting distances, the average weight ratios were 10.5 ± 1.3% (SD), 7.5 ± 1.2% (SD), and 6.1 ± 2.6% (SD) for AR legend; 9.8 ± 0.6% (SD), 5.3 ± 0.4% (SD), and 4.1 ± 0.9% (SD) for Maeuntan, and 10.3 ± 1.9% (SD), 8.3 ± 1.8% (SD), and 6.1 ± 0.9% (SD) for Jeockyoung. As shown, the weighed ratios of twigged hot pepper cultivars decreased with the planting distance, and the lowest weight ratio of twigged hot peppers was at a planting distance of 50 cm for all cultivars. Moreover, the results of the ANOVA on the effect of planting distance and cultivar on average weight ratios of twigged hot peppers showed significantly different effects as all p-values were <0.05,

but no interaction effect between planting distance and cultivar was found. Likewise, in a previous study, the whole to twigged ratios of AR Legend and Jeockyoung were 44.3% and 23.1%, respectively, respectively [9].

Table 7. Statistical analysis results for twigged hot pepper.

Cultivar	PD (cm)	M ± SD (%)	Weight (kg)	PCC	F-Value	*p*-Value
AR Legend	30	10.5 ± 1.3 b [(1)]	1.0 ± 0.1	−0.682 **	7.170	0.007
	40	7.5 ± 1.2 b	0.8 ± 0.1			
	50	6.1 ± 2.6 a	0.7 ± 0.1			
Maeuntan	30	9.8 ± 0.6 c	1.1 ± 0.1	−0.910 **	89.537	0.000
	40	5.3 ± 0.4 b	0.6 ± 0.1			
	50	4.1 ± 0.9 a	0.4 ± 0.1			
Jeockyoung	30	10.3 ± 1.9 b	0.9 ± 0.1	−0.723 **	8.228	0.004
	40	8.3 ± 1.8 ab	0.8 ± 0.1			
	50	6.1 ± 0.9 a	0.4 ± 0.1			
Group	**Source**	**DF**	**ANOVA SS**	**Mean Square**	**F-Value**	***p*-Value**
Twigged hot pepper	PD	2	208.481	104.241	39.641	0.000 **
	Cultivar	2	36.037	18.019	6.852	0.000 **
	PD*Cultivar	4	10.185	2.546	0.968	0.434
	Error	45	118.333	2.630		
	Total	53	373.037			

PD: Planting Distance; M: Mean; SD: Standard Deviation; PCC: Pearson's Correlation Coefficient; SS: Sum of Squares. [(1)]: Mean separation within columns by Duncan's Multiple Range test at $p = 0.05$. ** $p < 0.01$.

4. Discussion

Previous studies have reported that yield per plant was significantly influenced by planting distance. The yield per plant was also increased with an increase in planting distance [19,33,35]. However, increased planting distances caused a decrease in pepper yield because further planting distances meant fewer plants per unit area of hot pepper field. Therefore, the highest weight of marketable hot pepper was indicated at the 40 cm planting distance (Table 3), with 7.0 ± 0.2 kg (SD) for AR Legend, 9.5 ± 0.7 kg (SD) for Maeuntan, and 6.2 ± 0.5 kg (SD) for Jeockyoung obtained for all cultivars. Hence, we propose that the most suitable planting distance for mechanical harvesting of hot pepper is 40 cm.

The average weight ratio of damaged hot pepper was only related to the planting distance. The average weight ratio of lost hot pepper was significantly different when planting distance and cultivar were considered together. However, most damaged hot peppers were found during transportation to the loading bay causing too much force to be applied to the hot pepper. To improve the mechanical harvesting efficiency, the average weight ratio of damage should be reduced. The harvester consisted of three main components (threshing, transporting, and loading bay). A study to determine the specific harvester unit where the damage occurred needs to be conducted in the future with measurement of fruit damage. It was observed that the rotational speed of the helix had an effect on unharvested hot pepper rate in a previous study [9]. However, another factor was found in this study; according to Table 6, shortening the planting distance reduced the average weight ratio of unharvested hot peppers. Through the results of this study, the planting distance can also be said to affect the unharvested hot pepper rate. By controlling the planting distance and rotational speed of the helix, a more consistent performance for mechanically harvesting hot pepper can be conducted.

The average weight ratio of twigged hot pepper was decreased with further planting distance. The minimum weight ratio of twigged hot pepper was 4.1% in this study. Considering the twigged ratios of AR Legend and Jeockyoung were 44.3% and 23.1%, respectively, in a previous study [9], controlled planting distance seems to be a controlling factor for twigged hot pepper.

5. Conclusions

This study classified mechanically harvested hot peppers into five groups—marketable, damaged, lost, unharvested, and twigged. Evaluation of mechanical harvesting performances was conducted at three levels of planting distance with three different cultivars. We verified the effect of planting distance and cultivars on mechanical harvesting of hot pepper. The weight ratio of marketable hot pepper was highest at a planting distance of 50 cm for Maeuntan, followed by AR Legend and Jeockyoung. However, the yield of marketable hot pepper was highest at a planting distance of 40 cm. Moreover, the weight ratios of unharvested and twigged hot peppers were lowest at a planting distance of 50 cm for Maeuntan, followed by AR Legend and Jeockyoung. Therefore, we propose that increasing the planting distance provided enough time for the double helix to thresh the whole pepper plant, thereby reducing the intersection between the pepper plants and facilitating proper harvest. The proposed distance also resulted in increased weight ratios of marketable hot pepper and decreased weight ratios of damaged, unharvested, and twigged hot peppers. An interaction effect between planting distance and cultivar was found with the weight ratio of lost hot pepper. However, the damaged hot peppers were more related to the mechanical structure of the transporting component of the harvester; additional study is required with measurements of damage in each component of the machineTherefore, considering the yield of marketable hot pepper and the observed decrease in the weight ratio of unharvested and twigged hot peppers with the further planting distances used in this study, we propose the most suitable planting distance for mechanical harvesting of hot pepper is 40 cm.

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