Growth and Yield of Cucumber in a High-Wire Growing System with Different Training Methods

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Abstract

In this study, we analyzed European medium-sized cucumber (*Cucumis sativus* cv. Zeco) growth and yield in a high-wire growing system using different training methods in a smart greenhouse. The experimental treatments were applied as follows: 4P1S, four plants were trained on a single main stem; 4P2S, four plants were trained to one main stem plus a lateral stem from the seventh node in a slab; 3P2S, three plants were trained on two stems from the seventh node of a slab. The average daily drainage volume was lower in the 4P2S than other treatments with approximately 10% lower drainage ratio than that in 4P1S. The retained volume, the difference between the total irrigation and drainage volumes, was 154 $L \cdot m^{-2}$ for 4P1S, 199 $L \cdot m^{-2}$ for 4P2S, and 151 $L \cdot m^{-2}$ for 3P2S. Water use ($L \cdot kg^{-1}$ fruit) was in the order 4P2S (14.88) > 3P2S (12.34) ≥ 4P1S (12.00). The plant height, number of nodes, and length from the apex to the last flower were significantly lower in the 3P2S group than that of other treatments. Higher leaf dry weight was observed with the 4P1S treatment than with the 4P2S treatment. The number of stem nodes was highest in 4P1S, indicating a good relationship between this and the leaf dry weight. The number of fruits and fruits per plant was in the order of 3P2S > 4P2S > 4P1S, indicating that it was higher in the 6 stems per slab group than in the 4- or 8-stem groups. There was no significant difference in the fruit yield per unit area (m^2). It was 13.0 $kg \cdot m^{-2}$ for all treatments, which was about 1.6-fold higher than that from the greenhouse cultivation in Korea (7.96 $kg \cdot m^2$). It may be due to the cucumber variety with a high-wire growing system. The yield for each week was constant in the 4P1S group in accordance with the CSR (Cumulative Solar Radiation) level, whereas there was a large variation in the weekly yield harvested from plants grown with the 4P2S and 3P2S treatments. All the integrated results in the present study suggested that training one main stem per slab might be better for the European cucumber variety in terms of the water consumption, yield, and workload.

Additional key words: integrated solar radiation, recirculating hydroponics, retained volume, sap flow

Introduction

The Korea production of cucumber (*Cucumis sativus* cv. Zeco) in 2021 was 239,432 tons on 3,008 hectares of greenhouse with an average yield of 7.96 $kg \cdot m^2$ and 44,501 tons on 1,113 hectares of open field (KOSIS, 2021). The global production of cucumbers in 2021 was approximately 93,528,796

tons on 2,172,193 hectares, achieving an average yield of 4.31 kilograms (kg) per square meter (m^2). China produced 75,597,660 tons on 1,292,545 hectares, accounting for 80.8% of the global cucumber yield in 2021, and had an average yield of 5.69 kg·m^2. The Netherlands produced 440,440 tons on 690 hectares with an average yield of 63.8 kg·m^2, which had the best performance in the world, followed by Spain (9.66 kg·m^2), Turkey (7.29 kg·m^2), Greece (7.12 kg·m^2), Mexico (5.74 kg·m^2), Japan (5.27 kg·m^2), Russia (4.23 kg·m^2), Uzbekistan (3.48 kg·m^2), Kazakhstan (2.51 kg·m^2), and USA (1.78 kg·m^2) (FAOSTAT, 2023), indicating that the difference in productivity is extremely variable and large depending on the country.

Recently, Maeda and Ahn (2021) reviewed many studies related to cucumber production by considering environmental factors and training methods based on yield components. They discussed different training systems, pinching and lowering methods, and the effects of environmental factors, such as the temperature, humidity, CO_2 concentration, irrigation, and nutrition, on the yield and yield components. Higher productivity of cucumber can be achieved in controlled environments, like smart greenhouse; however, it is not yet predominant in many countries. The smart agriculture is expected to reach USD 25.4 billion by 2028 from an estimated USD 16.2 billion in 2023, at a compound annual growth rate of 9.4% from 2023 to 2028. The growth of the market can be attributed to the increasing global population creating pressure on the food supply system and surging use of modern technologies in agriculture (Markets and Markets, 2022). Recently, the export of greenhouse materials to Kazakhstan, Uzbekistan, and China has increased because of the high demand for smart greenhouses. Kim et al. (2020) stated that it is desirable to diagnose problems throughout the value chain, identify the necessary support areas, and proceed with cooperative projects for horticultural crops. Mongolia and Central Asia, which have meat-based diets, are implementing policies to balance nutrition through increased vegetable consumption; therefore, it is necessary to expand production by distributing cultivation and production technologies. In Mongolia, cucumber is one of vegetables that is normally produced in greenhouses from March to late September by individual farms and larger-scale entities, and its domestic production satisfies the total demand with an 84% self-sufficiency rate (Asian Development Bank, 2020). However, Mongolian cucumber production in 2021 was 6,161tons on 545 ha (FAOSTAT, 2023), approximately 4.13% of the total vegetable production in Mongolia (149 kilotons in 2022) (Mongolian Statistical Information Service, 2022). Because of the recent increase in the demand for fresh vegetables in the northern region, the supply of smarter greenhouses and technologies is urgently required. Recently, our research team investigated the weather conditions in the northern regions to develop a northern smart greenhouse model (Choi et al., 2023). The growth of cucumber in a smart greenhouse faces significant challenges owing to high labor costs, resulting in a requirement for higher yields through the year-round supply of high-quality fruits. For cucumber cultivation, a high-wire method can be used, in which the cucumber plants continue to grow upward and all fruits are produced at the main stem. It has been more than 20 years since the high-wire cultivation method was applied to pickling cucumber cultivars, in which growing pickling cucumbers on wires gave better results when compared with growing them on the ground, from the point of view of yield and quality (Tokatli and Özgur, 1999). Research on stem training methods for cucumber plants in Korea was conducted 20 years ago (Choi et al., 1999), and thus, little information is available. This study analyzed the growth and yield of cucumbers in a high-wire growing system using different training methods in a smart greenhouse.

Materials and Methods

The experiment was conducted at a smart greenhouse (latitude: 24.207500, longitude: 55.744720, area: 2,070 m^2, W: 60 m × L: 34.5 m × H: 5.7 m, PO film) from the 20th of July, 2022 to 10th of October, 2022. The UOS nutrient solution (University of Seoul solution), controlled at an electrical conductivity (EC) of $1.8-2.5$ dS·m^{-1} and pH of $5.5-6.0$ was supplied. The 100 times of stock solution A tank was composed as 5[Ca(NO$_3$)$_2$]NH$_4$NO$_3$ 86.4, KNO$_3$ 26.2, and Fe-DTPA 2.0 kg·1000 L^{-1}, and stock solution B tank was composed as KNO$_3$ 26.2, NH$_4$H$_2$PO$_4$ 5.13, KH$_2$PO$_4$ 13.5, and Mg(SO$_4$)$_2$· 7H$_2$O 49.2 kg·1000L^{-1} and micronutrients (H$_3$BO$_3$ 228.7, MnSO$_4$·H$_2$O 232.3, ZnSO$_4$·7H$_2$O 175.9, CuSO$_4$·5H$_2$O, 19.6, (NH4)MoO$_4$·2H$_2$O 12.6 kg·1000L^{-1}). The automated irrigation was monitored using the integrated radiation-automated recirculating system together with integrated environmental control systems (MAGMA+, Green Control System Ltd., Gwangju, Korea).

Seedlings of European medium-sized cucumber (*Cucumis sativus* cv. Zeco) on the rockwool cube were planted on coir slabs (100 × 20 × 10 cm, BIO GROW, dust:chip = 50:50 (v:v)) on July 20, 2022. The experimental treatments were applied as 4P1S, 4P2S, and 3P2S. For the 4P1S treatment, four plants were trained on a single main stem (2.3 stems·m^{-2}). The 4P2S treatment comprised four plants that were trained to one main stem plus a lateral stem from the seventh node in a slab (4.6 stems·m^{-2}) (Fig. 1). The 3P2S treatment was defined as three plants trained on two stems from the seventh node of a slab (3.4 stems·m^{-2}). Owing to the high-wire system, the heads of plants were regularly lowered to maintain the main stem production during the entire growing season. The measurement of plant growth was conducted three times on August 4 and 20 and September 18, and the final measurement with the final harvest was conducted on October 10. The results of the final measurements are presented in this paper. Plant height is the length from the stem base to the shoot apical point, and the number of node is counted, of which internode is longer than 2 cm. The length between the shoot apical point and closest fruit and the length between the shoot apical point and closest flower were measured. A Sap Flow sensor (Phyto-IT2020, 2Grow, Belgium) was attached to the base of the stem to monitor plant transpiration based on two

Fig. 1. Training methods applied in the present study, including one main stem plus one lateral stem (2S) (A) and one main stem (1S) (B) in a high-wire growing system (C). The lateral stem (A) was trained from the 7th node (x point) and fruits were produced from the 10th node.

replicates. The irrigation volume was measured using a separate drip pin in a beaker, and the drainage volume was measured by installing a film on the bottom of one slab to collect the drain water from the drain hole of the slab into the beaker. The drainage rate was calculated as follows: [drain rate (%) = 100 × (drainage volume per plant / daily irrigation volume per plant)]. The water volume required to produce 1 kg of fruit was calculated using the retained volume (total irrigation volume − total drainage volume). A randomized block design is applied for the experimental design. For the 4P1S, 4P2S, and 3P2S treatments, total 104, 104, and 78 plants in 26 slabs per gutter were transplanted, respectively, and two of the 26 slabs were considered 2 replicates for each treatment. Measurements of fruit quantity, weight, and yield were conducted with a randomized complete block design and 2 replications. Plant measurements were conducted based on 3 replications, and the 3 replicates of each treatment are assigned randomly to the 2 plots.

Results and Discussion

The highest air temperature inside the greenhouse was 35°C in July, August, and September, and it was approximately 32°C in October. Whereas the highest temperature outside the greenhouse was 48°C in August, it was 41.5°C in October. The internal temperature was lower, by approximately 9.3, 11.7, 9.1, and 7.2°C, than the external temperature in July, August, September, and October, respectively. The average relative humidity (RH) inside the greenhouse was 76.9, 79.6, 81.5, and 81.9% in July, August, September, and October, respectively, the average humidity deficit (HD) was 5.1, 4.5, 4.9, and 4.7 $g \cdot m^{-3}$, and the average carbon dioxide (CO_2) concentration was 327, 347, 390, and 413 $\mu mol \cdot mol^{-1}$, respectively. The maximum solar radiation intensity (SI) was 1,134, 1,090, 982, and 918 $w \cdot m^{-2}$ in July, August, September, and October, respectively, and the highest integrated solar radiation (ISR) was 2,554, 2,610, 2,574, and 2,240 $J \cdot cm^{-2}$ respectively (Table 1). During the day time, the RH was ranged between 80 and 88%, and HD was maintained at 4.0 $g \cdot m^{-3}$ (Table 2). The HD is usually maintained at the level between 3 and 7 $g \cdot m^{-3}$, for which, the RH should be maintained between 80 and 90% at a 30°C-air temperature. Kittas et al. (2005) emphasized that plants grown at higher

Table 1. Maximum, minimum, and average of air temperature (AT), relative humidity (RH), humidity deficit (HD), carbon dioxide (CO_2) concentration, solar irradiance (SI), and integrated solar radiation (ISR)

Months		Greenhouse air				Outside air		
		AT (°C)	RH (%)	HD ($g \cdot m^{-3}$)	CO_2 ($\mu mol \cdot mol^{-1}$)	AT (°C)	SI ($W \cdot m^{-2}$)	ISR ($J \cdot cm^{-2} \cdot day^{-1}$)
	Max.	35.0	90.9	14.8	347	43.5	1,134	2,554
Jul.	Min.	20.0	60.7	0.5	309	26.7	0	0
	Ave.	26.2	76.9	5.1	327	35.5	246	2,125
	Max.	34.8	98.4	18.0	493	48.0	1,090	2,610
Aug.	Min.	19.8	50.6	0.2	252	26.8	0	0
	Ave.	25.4	79.6	4.5	347	37.1	277	2,395
	Max.	35.0	97.8	18.2	547	43.8	982	2,574
Sept.	Min.	19.3	48.1	0.0	303	24.8	0	0
	Ave.	25.2	81.5	4.9	390	34.3	265	2,299
	Max.	31.8	97.8	13.2	562	41.5	918	2,240
Oct.	Min.	17.2	49.5	0.3	309	21.5	0	0
	Ave.	24.4	81.9	4.7	413	31.6	243	2,149

temperatures require higher humidity, which is associated with plant transpiration. Optimal vapor pressure deficit (VPD) values are recommended in the range of 0.3 to 1.0 kPa (Shamshiri et al, 2018), and for example, a VPD of 0.85 kPa can result from different combinations of air temperature and RH (i.e., T = 15°C and RH = 50% or T = 34°C and RH = 84%). Therefore, greenhouse climate conditions seemed to be maintained at the optimal level for proper plant transpiration, as shown based on the sap flow (SF) being maximized at 149 g·h^{-1} (Table 2).

The average daily drainage volume and ratio were lower in the 4P2S group than those in the other treatments. The drainage ratio in the 4P2S was approximately 10% lower than that of 4P1S, and the drainage ratio was higher than that of 3P2S (Table 3). The retained volume, which was the difference between the total irrigation and drainage volumes, was

Table 2. Hourly average of air temperatures (Air temp.) of internal and external (Ext.) greenhouse, relative humidity (RH), humidity deficit (HD), carbon dioxide (CO_2), solar irradiance (SI), absolute humidity (AH) and sap flow (SF) of cucumber stem between the 20th of July and 12th of October, 2022

Hour	Air temp. (°C)	RH (%)	Ext. Air temp. (°C)	Ext. SI (w·m^{-2})	CO_2 (μmol·mol^{-1})	HD (g·m^{-3})	AH (g·m^{-3})	SF (g·h^{-1})
0	19.8	91.0	25.3	0.0	439	1.6	15.8	5.04
1	19.6	91.9	24.4	0.0	447	1.4	15.7	5.05
2	19.4	92.2	23.9	0.0	455	1.4	15.6	1.81
3	19.1	92.7	23.4	0.0	460	1.3	15.4	2.24
4	19.0	93.0	22.9	0.0	464	1.2	15.3	3.96
5	19.1	93.1	22.6	0.1	471	1.2	15.4	5.34
6	19.1	93.4	22.5	10.9	476	1.2	15.5	8.63
7	20.5	90.1	23.7	113	456	1.9	16.3	28.0
8	24.6	82.1	26.3	275	391	4.1	19.1	105
9	26.4	83.7	28.7	480	343	4.2	21.6	101
10	26.5	86.1	30.3	673	352	3.6	22.4	149
11	26.9	85.9	31.7	801	346	3.8	22.9	138
12	28.9	86.9	32.8	866	341	3.9	26.1	144
13	29.2	86.8	33.7	832	340	4.1	26.5	138
14	29.0	87.6	34.2	711	340	3.7	26.3	134
15	28.4	85.6	34.6	640	341	4.1	25.1	104
16	27.5	83.8	34.5	459	343	4.4	23.0	64.3
17	26.3	81.3	33.9	258	347	4.8	21.0	37.5
18	24.6	79.7	32.6	65.2	360	4.7	18.5	20.5
19	24.0	80.7	30.8	0.1	384	4.3	18.0	13.5
20	21.9	88.5	29.4	0.0	400	2.2	17.6	8.16
21	20.6	87.8	28.2	0.0	411	2.3	15.9	6.33
22	20.3	89.1	27.2	0.0	423	2.0	16.0	5.61
23	20.1	90.3	26.2	0.0	431	1.7	15.9	5.17

Table 3. Daily irrigation and drainage volumes per plant and the pH and EC affected by different training methods

Training[z]	Daily irrigation			Daily drainage			
	pH	EC (dS·m^{-1})	Vol (mL·plant^{-1})	pH	EC	Vol (mL·plant^{-1})	Drainage ratio (%)
4P1S	6.27 a[y][x]	2.22 b	1,601 a	6.84 a	2.25 a	523 b	32.50 a
4P2S	6.27 a	2.23 b	1,731 a	6.61 b	2.12 a	356 c	20.49 c
3P2S	6.29 a	2.27 a	1,666 a	6.36 b	2.42 a	621 a	27.93 b

[z]4P1S: four plants per slab with one main stem; 4P2S: four plants per slab with one main stem and one lateral stem trained from the seventh node; 3P2S: three plants per slab with one main stem and one lateral stem trained from the seventh node.
[y]Means with different letter within the column is significantly different by Duncan's multiple range test at $p < 0.05$.
[x]Each value is the mean of 2 replications.

154 L·m^{-2} for the 4P1S, 199 L·m^{-2} for 4P2S, and 151 L·m^{-2} for 3P2S. As there was no significant difference in the fruit yield per unit area (m^2) (Tables 6), the 4P2S treatment required more water to produce 1 kg of fruit. Water use (L·kg^{-1}fruit) was higher in the 4P2S (14.88) than those in the 3P2S (12.34) and 4P1S (12.00) (Table 4).

The plant height, node number, and the length from the shoot apical point to the closest flower were significantly lower in the 3P2S treatment. Female flowers of Korean cucumber variety are normally produced at the location at the 40 − 50 cm apart from the shoot apical point (Jeong, 2001). In the 3P2S treatment, the distance between the shoot apical point to closest female flower was about 16 cm, whereas it was about 70 cm in the other treatments. The A higher leaf dry weight was observed in the 4P1S treatment group than in the 4P2S treatment group. The number of stem nodes was highest in 4P1S, indicating a good relationship between the number of stem nodes and leaf dry weight (Table 5). The number of fruits per plant was in the order of 3P2S > 4P2S > 4P1S, indicating that it was higher with six stems per slab than with four or eight stems.

There was no significant difference in the fruit yield per unit area. It was 13.0 kg·m^{-2} for all treatments (Table 6), which was about 1.6-fold higher than that from the greenhouse cultivation in Korea (7.96 kg·m^2). It may be due to the cucumber variety (European medium-sized variety) different from Korean variety with the high-wire growing system. Fig. 2 shows weekly yield and weekly cumulative solar radiation (CSR). The yield for each week was constant in the 4P1S group in accordance with the CSR level, whereas there was a large variation in the weekly yield harvested from plants grown with

Table 4. Total irrigation, drainage and retained volumes per plant and area unit and water use affected with different training methods during the entire growing period

Training[z]	Total irrigation volume	Total drainage volume	Total irrigation (A)	Total drainage (B)	Retained volume (A − B)	Water use
	(mL·plant^{-1})		(mL·m^{-2})			(L·kg^{-1}fruit)
4P1S	99,242 a[y][x]	32,441 a	228,257 a	74,615 a	153,642 b	12.00 b
4P2S	109,080 a	22,414 b	250,884 a	51,551 b	199,333 a	14.88 a
3P2S	103,314 a	37,858 a	237,622 a	87,073 a	150,550 b	12.34 b

[z]4P1S: 2.3 stems·m^{-2}, 4P2S: 4.6 stems·m^{-2}, 3P2S: 3.4 stems·m^{-2}.
[y]Means with different letter within the column is significantly different by Duncan's multiple range test at $p < 0.05$.
[x]Each value is the mean of 2 replications.

Table 5. Plant growth characteristics affected by different training methods

Training[z]	Plant height	Total node number (no·plant^{-1})	Shoot apical point to closest fruit Distance (cm)	Shoot apical point to closest fruit Node number (no.)	Shoot apical point to closest female flower Distance (cm)	Shoot apical point to closest female flower Node number (no.)	Fresh weight (g·plant^{-1}) Stem	Fresh weight (g·plant^{-1}) Leaf	Dry weight (g·plant^{-1}) Stem	Dry weight (g·plant^{-1}) Leaf
4P1S	604 ab[y][x]	51.67 a	213 a	19.00 a	69.33 a	7.33 a	515 a	420 a	37.00 a	34.03 a
4P2S	566 b	43.00 b	199 a	16.33 a	73.00 a	8.00 a	364 bc	316 ab	24.97 b	23.03 c
3P2S	443 c	33.33 c	217 a	17.00 a	15.67 b	1.33 b	317 c	267 b	24.23 b	25.47 bc

[z]4P1S: four plants per slab with one main stem; 4P2S: four plants per slab with one main stem and one lateral stem trained from the seventh node, 3P2S: three plants per slab with one main stem and one lateral stem trained from the seventh node.
[y]Means with different letter within the column is significantly different by Duncan's multiple range test at $p < 0.05$.
[x]Each value is the mean of 3 replications.

the 4P2S and 3P2S treatments, regardless of CSR level. This result indicated that, although there was no difference in the yield per unit area according to the training method, a certain training method could lead to yield fluctuations for a certain variety that might not be advantageous for distribution. It was ideal to apply the lateral vine method to the 'Zeco' variety because the lateral shoot was rarely developed. Notably, the yield is correlated with the average daily solar radiation in greenhouses; however, training methods could lead to different results.

The 4P1S treatment, which had the highest number of nodes and leaf dry weights, produced a fruit yield similar to that with the other treatments. When harvesting from only the main stem (e.g., 4P1S), if the main stem extends beyond a certain length, it must be lowered. Thus, the leaves located underneath receive light intensity close to the compensation point owing to shielding. In the present study, the daily average irradiance was about 1,000 $W·m^{-2}$. A recent our study revealed that the average daily solar radiation of the Dalanzadgad of Mongolia for 36 years ranged to 372 $W·m^{-2}$ with the 2,836 hours of annual sunshine (Choi et al., 2023). Therefore, it is necessary to utilize as much light as possible by properly training main or secondary stems during periods of low temperature and low light intensity. Our previous study resulted a 3.2 $kg·m^{-2}$ of cucumber yield (Korean 'Bakdadaki' variety) in a Korea smart greenhouse located in Ulaanbaatar during the growing period from July to October. The 'Bekdadaki' variety is not highly preferred by Mongolian, therefore studies on the selection of various varieties and its appropriate training methods are needed.

Table 6. Yield characteristics affected by different training methods

Stem training	Fruit weight (kg·plant[-1])	Fruit number (ea·plant[-1])	Fruit weight (kg·stem[-1])	Fruit number (ea·stem[-1])	Fruit weight (kg·m^{-2})	Fruit number (ea·m^{-2})
4P1S	5.61 b[yx]	58.08 b	5.61 a	58.08 a	12.9 a[z]	134 a
4P2S	5.65 b	60.21 b	2.82 b	30.10 b	13.0 a[y]	138 a
3P2S	7.47 a	77.54 a	3.74 b	38.77 b	13.0 a[x]	135 a

[z]4P1S: 2.3 stems·m^{-2}, 4P2S: 4.6 stems·m^{-2}, 3P2S: 3.4 stems·m^{-2}.
[y]Means with different letter within the column is significantly different by Duncan's multiple range test at $p < 0.05$.
[x]Each value is the mean of 3 replications.
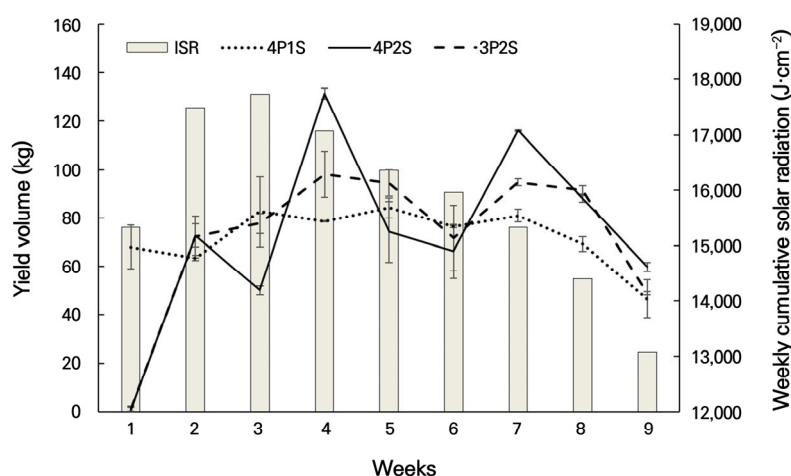
Fig. 2. Weekly yields of cucumber harvested from the plants grown on the each of gutters under the different training methods, including 4P1S (104 plants per gutter), 4P2S (104 plants per gutter), and 3P2S (78 plants per gutter), and weekly cumulative solar radiation (CSR). Measurements were conducted from August 11, 2022, to October 11, 2022. Error bars indicate the standard deviation of the mean value for two replicates.

In addition to that, for the selection of training method, a workload should be considered in terms of working time. Choi et al. (1999) determined the effects of different training methods on the growth and yield of white-spine cucumbers (*Cucumis sativus* L. cv. Sharp-1), in which three training methods were applied as follows: only one main vine, one main vine and one lateral vine from the 10 to 13th nodes, and 3 or 4 lateral vines from the 10th node (the main vine was pinched at the 20th node, and the lateral vine was pinched at the second or third node). The results showed that the ratio of the leaf area in the lower part of the plant was higher for the main vine and main plus lateral vine treatments than for the lateral vine treatment, reducing photosynthesis efficiency. The total and marketable fruit yields were higher with the lateral training method than with the other methods, with a higher workload in the main plus lateral vine training methods. These results suggested that the main vine plus lateral vine treatment required more effort than the main vine treatment, as it was the same as the two main vines, whereas the lateral vine treatment tool time to prune but required less working time to lower the vine than the main vine method. Samba et al. (2023) examined the growth and yield of cucumber under two different training methods, including lowering training (LT) and pinching training (PT), in which a significantly higher total stem length (10.9 m), number of nodes (133), total yield (15.4 kg·m^{-2}), and marketable yield per unit area (13.8 kg·m^{-2}) were recorded with the LT treatment. Because the work required to remove old leaves and harvest fruits was simplified with the LT treatment, the authors postulated that the LT method could be effective for the automation of old leaf removal and fruit picking by robots in the future.

All the integrated results in the present study suggested that training one main stem per slab might be better for the European cucumber variety in terms of the water consumption, yield, and workload.

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