A Comparison Between Modified-umbrella and High-wire Trellising Systems in a Low-profile Greenhouse for Hydroponic Beit Alpha Cucumber

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Abstract. The production of Beit Alpha cucumber (*Cucumis sativus*) in hydroponic systems has increased in popularity since the early 2000s, along with the use of high-wire trellising systems. Some farmers claim the high-wire trellising systems, also known as drop-and-lean trellising, result in a more consistent weekly yield than umbrella or modified-umbrella systems. This study compared the high-wire and modified-umbrella trellising systems both using a 7 ft top wire and 4 plants/m^2 plant density. The fruit weight and number of fruit per plant were significantly greater using the modified-umbrella trellising system, with the number of fruit being about twice as high as the high-wire trellising system. Consistency of yields was also measured for both systems and found to peak at ~5 to 7 weeks after the start of harvest using both trellising systems. However, peak yields using the modified-umbrella trellising system followed a quadratic curve, implying that the high-wire trellising system results in more consistent yields. Differences in yield and harvest consistency were likely related to light penetration of the plant canopy. Growers using low-profile greenhouses can expect lower yields and more consistent harvests using the high-wire trellising system. Yields may be improved using a higher plant density. Alternatively, succession planting on a 5- to 7-week interval can improve harvest consistency using a modified-umbrella trellising system.

In hydroponic systems, plant growth and development are supported by a water-based nutrient solution with or without inert or aggregate media for root anchorage (Sharma et al. 2018). Hydroponic vegetable production is increasing in popularity worldwide partly because, compared with outdoor cultivation, water, fertilizer, production area, and other resources can be used more efficiently, and production cycles can be shorter and repeated year-round (Sharma et al. 2018). Cucumber (*Cucumis sativus*) is a major greenhouse hydroponic crop in the United States (Shaw et al. 2007) making up the second-highest sales (after tomato, *Solanum lycopersicum*) at \$78 million (Produce Grower 2016).

The vegetable farming industry in Pennsylvania, USA, primarily consists of small-scale diversified farms selling through direct markets [US Department of Agriculture (USDA), National Agricultural Statistics Service 2017]. According to the most recent USDA Census of Agriculture (2017), Pennsylvania vegetable farms averaged about 9 acres in size, with 4062 farms comprising 36,569 acres. This makes Pennsylvania unique because, compared with other states, it is composed of many diversified farms with small areas devoted to any one crop. For example, 1510 farms grew fresh market tomatoes on 1616 acres, averaging 1 acre on each farm (US Department of Agriculture, National Agricultural Statistics Service 2022). In addition, most Pennsylvania farms had sales of less than \$100,000 annually between 2017 and 2021 (US Department of Agriculture, National Agricultural Statistics Service 2022). Pennsylvania agriculture is made up of many small-acreage producers; however, most hydroponic vegetable crop research is targeted for larger-scale production. Research is limited on alternative production methods for small-scale producers in a hydroponic setting.

For example, the high-wire trellising system was developed in a high-profile (>3.7 m) greenhouse. Through our work as extension specialists, we know of a few high-profile greenhouses using cutting-edge technology in Pennsylvania. Most greenhouses are on small-scale farms and are single-span, low-profile, low-technology, and low-cost facilities. It is currently unknown if high-wire trellising systems are suited to the low-profile greenhouses that predominate the Pennsylvania greenhouse industry (Von Zabeltitz 2010). High-profile greenhouses have large volumes that can accommodate vertical plant growth. Such greenhouses have more stable climatic conditions because of improved ventilation efficiency, which can produce higher yield and crop quality (Von Zabeltitz 2011). However, they also have decreased air temperatures, resulting in increased heating requirements (Fatnassi et al. 2017). Therefore, new technologies evaluated in high-profile greenhouses must be vetted for low-profile facilities to be meaningful for most Pennsylvania farmers.

European cucumber dominated hydroponic production in the United States until Beit Alpha types were introduced in Florida in 2000 (Shaw et al. 2000). Since then, as Shaw et al. (2004) predicted, Beit Alpha cucumber has gained prominence in the marketplace, likely due to a combination of fruit quality and production characteristics. Beit Alpha cucumber is adapted to wider environmental conditions than European types, including having a production temperature range of 15 to 40 °C (Shaw et al. 2000). Beit Alpha plants also produce several flowers at each node, resulting in a higher yield than European cucumbers, which produce a single flower at each node (Shaw et al. 2007). In addition, the fruit have thin excocarps. This can be a desirable trait because it

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allows for pleasant consumption without requiring the labor of peeling. Further, unlike European types, Beit Alphas do not require individual shrink wrapping to maintain market quality (Shaw et al. 2007).

Although improvements in cultivar selection contribute to improving vegetable production, pruning and other management methods can also have major implications on yields (Sharma et al. 2018). Currently, much of the hydroponic cucumber production worldwide relies on the umbrella (Shaw et al. 2000) or modified-umbrella trellising system (Resh 2013) with an overhead wire at roughly 2 m high (Resh 2013). The basic technique for these systems is that plants are trained to a single main stem, with or without shortened lateral branches. Once the main stem reaches the overhead support wire, it and/or lateral branches are directed downward on either side of the main stem, creating the "umbrella" (Papadopoulos 1994).

Within the past 10 years or so, many Pennsylvania farmers have shifted to using the high-wire trellising system in high- and low-profile greenhouses. Although there is no standard definition for the dimensions of a high-profile or low-profile greenhouse, high-profile greenhouses generally have increased vertical space resulting in extra production area. Here, we will refer to low-profile greenhouses as having a gutter height below 3 m and high-profile greenhouses with gutter heights greater than 3 m.

High-wire systems for cucumber are similar to the drop-and-lean trellising system commonly used for hydroponic tomatoes. In high-wire systems, plants are supported by a string and trained to a single stem by removing all lateral branches. Upon reaching the overhead support wire, the string is lengthened and moved about a meter farther along the wire. This creates more area on the string to support additional plant growth. This process is repeated as the plant again reaches the overhead wire (Bame and Bullen 2007; Hao et al. 2007). The high-wire system was introduced in the late 1990s in the Netherlands through experimentation in a high-profile (3.5 m top wire height) greenhouse (Welles 1999) and has gained popularity to meet the need for year-round high-quality cucumber (Hao et al. 2007). Pennsylvania farmers have mentioned the benefits of more consistent weekly yield and ease of harvest as reasons for adopting high-wire trellising.

In this study, two methods of trellising, modified umbrella and high wire, were compared in hydroponic Beit Alpha cucumber production in a low-profile greenhouse. Differences in yields were evaluated by measuring the mean number of cucumbers produced and the mean weight of fruit. Consistency of yield was also measured by evaluating the weekly cucumber harvest throughout the growing season. It was hypothesized that using the high-wire system would result in equal or lower yields than the modified-umbrella system but have a more consistent weekly yield.

Materials and methods

This study was repeated three times at Pennsylvania State University, University Park, PA, USA, in a 30 ft × 40 ft polycarbonate-covered gothic greenhouse with a gutter height of 8 ft in about the spring (Mar–Jun), summer (Jun–Sep), and fall (Sep–Dec) of 2019 (Table 1). Throughout the study, the greenhouse was heated when air temperatures reached 20 °C and cooled at 27 °C during the day, and heated and cooled at 18 °C and 26 °C, respectively, at night. Relative humidity was set at 69%. Supplemental red/blue spectrum light-emitting diode (LED) lighting, placed 7 ft above and parallel to plant rows, was provided between 6 AM and 8 PM when natural light levels were below 800 µmol. LED lights were turned off when natural light levels were above 1000 µmol.

Plants were grown in 79-L bags of soilless medium (Metro-mix 852 RSI, Sun Gro Horticulture, Agawam, MA, USA) laid flat, side-by-side on the long end and with five small holes punctured in the bottom of each bag for drainage. Four 6-m^2 treatment rows, consisting of 12 bags each, were spaced 3 ft center-to-center. We grew 'Socrates' (Johnny's Selected Seeds, Winslow, ME, USA), a Beit Alpha, gynoecious, parthenocarpic, hydroponic cucumber cultivar, for all evaluations of the study. Two 3- to 4-week-old transplants were spaced 2 ft apart within each bag, creating a double row with a density of 4 plants/m^2.

A drip stake irrigation system, with one emitter per plant, supplied 4 L of a nutrient solution to each plant daily. The nutrient solution was made with potable water and supplemental nutrients using a 14-gal/min fertilizer injector (D14MZ2; Dosatron International LLC, Clearwater, FL, USA) following the Hydro-Gardens (Hydro-Gardens, Colorado Springs, CO, USA) program. The program consisted of applying 227 g of 8N–7P–30K, 227 g of calcium nitrate, and 142 g of magnesium sulfate to 879 L of water for the final nutrient concentrations listed in Table 2. The target electrical conductivity of the nutrient solution was 2.8 dS/m (2.2 dS/m for the Hydro-Gardens program plus 0.6 dS/m for the potable water), and the pH was between 6.4 and 6.7. Nutrients were not recirculated, and fertigation occurred twice daily.

The two treatments in the study were the high-wire and modified-umbrella trellising systems. For both treatments, plants were supported by trellis clips (WPROICHD, Baoan Dist. Shenzhen Guangdong, China) to a vertical polypropylene string that was hooked to a 9-gauge galvanized top wire placed 7 ft above and parallel to each planting row. In addition, flower buds and secondary branches were removed from the first four nodes of all plants. We did not cluster prune regardless of the trellising treatment.

Plants grown using the high-wire system were trained to a single stem by removing all lateral branches. Once the stem reached the top wire, the lowermost leaves were removed. Then, the string was lengthened to support additional plant growth, and the hook was moved ~1 m farther along the wire. As the plant again reached the overhead wire, this process was repeated.

Table 1. Transplanting and harvest dates for the hydroponic cucumber trellising systems evaluation conducted in the spring, summer, and fall of 2019 at University Park, PA, USA.

Expt. dates	Spring	Summer	Fall
Transplanting date	8 Feb	28 May	27 Sep
First harvest date	7 Mar	28 Jun	25 Oct
Final harvest date	14 May	26 Aug	6 Dec

Table 2. The concentration of nutrients in the Hydro-Gardens fertility program and potable water supplied to hydroponic cucumber plants grown in a trellising systems evaluation in University Park, PA, USA, in 2019.

Nutrient	Hydro-Gardens fertility Program[i] (ppm)[ii]	Potable water (ppm)
Nitrogen	139.26[iii]	34.00
Phosphorus	94.99	15.42
Potassium	215.45	29.65
Calcium	112.19	43.20
Magnesium	35.19	23.03
Manganese	2.37	0.01
Iron	1.19	<0.10
Molybdenum	0.60	<0.010
Boron	0.30	0.03
Copper	0.30	0.03
Zinc	0.30	0.08

[i] Hydro-Gardens, Colorado Springs, CO, USA.
[ii] 1 ppm = 1 mg·L^{-1}.
[iii] Values determined by Pennsylvania State University's Agricultural Analytical Services Laboratory, University Park, PA, USA.

In the modified-umbrella treatment, secondary branches were pruned to two nodes, whereas in a traditional umbrella system, all lateral branches are removed. Once the main stem reached the overhead support wire, the apical meristem was removed. The "umbrella" was formed by allowing two secondary branches from the top of the plant to drape downward on either side of the main stem. Tertiary branches were pruned to two nodes on the "umbrella" branches. The lowermost leaves were removed when they became chlorotic or necrotic.

Cucumbers were harvested twice weekly, and collected individually when the fruit were ∼15 to 20 cm long and had only slight ribbing. Harvest began about 8 weeks after transplanting (Table 1) and occurred for 9, 8, and 6 weeks for the spring, summer, and fall evaluations, respectively. Data were measured from each plot during each season. Fruit were categorized as marketable or unmarketable. However, almost no fruit were unmarketable. Marketable yields were measured by recording the weight and number of harvested marketable fruit.

Experimental design and analysis. The two trellising treatments were arranged in a randomized complete block design with two replications in each evaluation (spring, summer, and fall). Marketable yield data were pooled over the three evaluations and analyzed using the GLIMMIX procedure (SAS version 9.4; SAS Institute Inc., Cary, NC, USA). When probability values were less than or equal to 0.05, means were separated using the slice option to perform Tukey's multiple comparison test. Polynomial trendlines and R^2 values for weekly yield over all replications (48 plants) were determined for the spring and summer evaluations using Excel (Excel version 16.0, Microsoft Company, Redmond, WA, USA). The fall evaluation was excluded from the cumulative weekly analysis because of the shorter harvest period compared with the spring and summer evaluations.

Table 3. The marketable mean number of cucumbers harvested from the modified-umbrella and high-wire trellising systems in the spring, summer, or fall of 2019 in University Park, PA, USA.

	Mean marketable yield (no./plant)
Trellising system	
Modified umbrella	30.5 a[i]
High-wire	16.6 b
Season	
Spring	32.0 a
Summer	30.5 a
Fall	8.0 b

[i] Values within a column followed by different letters within a trellising system or season are statistically significant at $P \geq 0.05$.

Results

The interaction between the trellising system and season was not significant for the mean number of marketable cucumber ($P = 0.094$). The largest mean number of fruits were harvested from plants grown with the modified-umbrella vs. the high-wire system in the spring and summer compared with the fall evaluation (Table 3).

The interaction between the trellising system and season was significant for the mean weight of marketable cucumber ($P = 0.041$). Almost twice as many cucumbers were harvested from plants grown using the modified-umbrella compared with the high-wire trellising system (Table 4). However, in the fall experiment, mean yields were not significantly different between the trellising systems. In addition, the mean weight of harvested cucumber in the fall was lower than in the spring and summer evaluations.

The total number of marketable cucumbers harvested weekly over all replications (48 plants) was more consistent when using the high-wire system than the modified-umbrella system (Fig. 1). The weekly number of fruit harvested from the modified-umbrella system in the spring and summer evaluations followed a parabolic path, peaking after about week 5 or 7 of harvest with R^2 values of 0.6627 and 0.8299, respectively. The weekly number of fruit harvested from the high-wire trellising system in the spring and summer evaluations followed a less steep parabolic path with R^2 values of 0.763 and 0.4729, respectively. The total weekly weight of marketable cucumber

Table 4. The mean marketable weight of cucumber harvested from the modified-umbrella and high-wire trellising systems in the spring, summer, or fall of 2019 in University Park, PA, USA.

Season	Trellising system	Mean marketable yield (kg/plant)[i]
Spring	Modified umbrella	7.8 b[ii]
	High-wire	4.9 c
Summer	Modified umbrella	11.2 a
	High-wire	5.0 c
Fall	Modified umbrella	3.7 d
	High-wire	1.1 d

[i] 1 kg = 2.2046 lb.
[ii] Values with a column followed by different letters are statistically significant at $P \geq 0.05$.

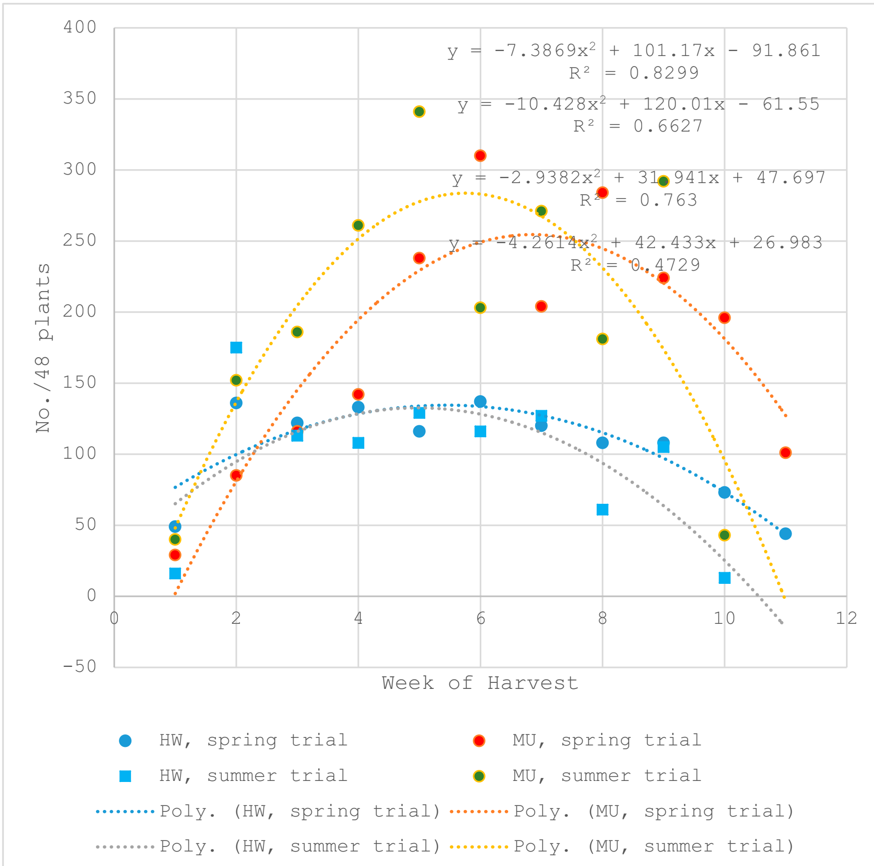

Fig. 1. The weekly number of marketable cucumbers harvested (48 plants) and polynomial (Poly.) trendlines for plants grown using a modified-umbrella (MU) or high-wire (HW) trellising system in the spring and summer of 2019 at University Park, PA, USA.

over all replications followed similar trendlines (data not shown).

Discussion

As hypothesized, using the modified-umbrella trellising system resulted in more marketable fruit, roughly double the amount, than the high-wire system. Fruit are produced at each node. In the modified-umbrella system, secondary branches were pruned after two nodes, whereas secondary branches were removed entirely in the high-wire system. These additional secondary branches allowed the potential for more fruit to be produced. In addition, once the main stem reached the top wire in the modified-umbrella trellising system, two secondary branches were trained to become each side of the "umbrella." This again created the potential for increased yield, as fruit could be produced on these lateral branches. Based on the number of plant nodes, the number of fruit produced could have been more than three times higher from the modified-umbrella compared with the high-wire trellising system.

This study was conducted across three growing seasons to observe any seasonal effect on the treatments. Although there was no effect by season on treatment, the results do show high variation in the yields depending on the season. For example, the total yields during the fall evaluation were harvested for 6 weeks and yields from the modified-umbrella trellising system were 3.7 kg and 1.1 kg for the high-wire system, although the summer evaluation was harvested for 8 weeks and yields from the modified-umbrella trellising system were 11.2 and 5.0 from the high-wire system (Table 4). These results are likely due to decreased natural light levels in the different seasons as cucumbers are fast-growing plants with high light requirements (Ding et al. 2020).

Leaf area index (LAI) for greenhouse vertical cucumber production is between 3 and 3.5 for optimal light penetration, photosynthetic activity, and air circulation. This equals ~13 to 16 leaves per plant (Xiaolei and Zhifeng 2004). We did not measure LAI. However, we observed fewer leaves with the high-wire system than the modified-umbrella system because the top wire height and row length limited vertical growth. In fact, this observation in commercial hydroponic facilities was a driver for conducting this study. Ding et al. (2020) reported 15 leaves resulted in a cucumber plant height of ~5 ft with a high-wire trellising system and an LAI of ~2.69 using a plant density of 2.8 stems/m^2. In our experiment, the top wire was set at 2.1 m, indicating that we likely had at least 15 leaves. However, we used a plant density of 4 stems/m^2, suggesting our LAI was near optimal for the high-wire trellising treatment.

A study using high-wire trellising systems reported the first four leaves nearest the terminal meristem received the most light. However, the next 11 to 16 leaves had the highest photosynthetic activity because they were fully mature, received adequate light (Xiaolei and Zhifeng 2004), and had higher chlorophyll a, chlorophyll b, and carotenoid contents (Ding et al. 2020). Older leaves were almost photosynthetically unfunctional (Xiaolei and Zhifeng 2004). Using the modified-umbrella trellising system, the apical meristems were directed downward once the plants reached the top wire. This likely increased the light levels reaching the most photosynthetically functional leaves. Notwithstanding, the "umbrella" branches increased stem density to 12 stems/m^2, very likely increasing the LAI to above optimum, resulting in fruit abortion and reduced potential fruit yield.

Another factor suggesting LAI was above optimum when using the modified-umbrella trellising system is found in fruit weight. Fruit weight was higher in the summer and spring evaluations when using the modified-umbrella compared with the high-wire system. We believe the lack of significant differences observed in the fall trial was due to the shorter days and lower natural light levels, resulting in a shorter crop cycle than the summer and spring evaluations.

Fruit weight in the summer and spring evaluations were *less* than twice as high in the modified-umbrella compared with the high-wire system; however, the number of fruit was roughly twice as high. This indicates that individual fruit weight and fruit weight per plant were higher from the high-wire compared with the modified-umbrella trellising system. Modeling has revealed that when solar radiation increases by 8%, individual fruit weight increases by 3% (Marcelis and Gijzen 1998). When using umbrella trellising systems, limited light reaches the bottom of the plant canopy, and as a result, lower leaves have a limited contribution to plant growth and development (Hao et al. 2007). In addition, the plant canopy shaded many fruit, causing poorer fruit quality (Hao et al. 2007).

A lower plant density in the modified-umbrella treatment may have resulted in more light penetration into the canopy and a more optimal LAI. Although the number of potential fruit would be less, fruit abortion would be reduced and may result in more harvested fruit. Fewer plants would also reduce production costs. In addition, with a lower plant density and increased light penetration, the fruit exocarp may contain higher chlorophyll levels and, as a result, be of higher quality, as Hao and Papadopoulos (1999) reported for a European cucumber. This is an area warranting future study.

Weekly yield peaked 5 or 7 weeks after the start of harvest and lasted between 3 and 4 weeks when using the modified-umbrella system. Yield was more uniform when using the high-wire system. Uniformity can facilitate forecasting and matching yield to market demand. In the United States, food waste throughout the food supply has been estimated to be 30% to 40% (US Food and Drug Administration 2020). One cause of on-farm postharvest food loss is fluctuating yields leading to produce quantities above contractual obligations (Porat et al. 2018). Therefore, uniform harvests can lead to decreased postharvest losses. Fluctuations in yield from plants trained with the umbrella system have been attributed to uneven light distribution within plant canopies (Hao et al. 2007) and is related to LAI. Using high-wire trellising systems results in more uniform light levels in plant canopies (Hao et al. 2007). Sequential planting on 3- or 4-week production cycles could be used to even out the harvest peak and result in a more uniform yield using the modified-umbrella trellising system.

As farmers with high-profile greenhouses have noted, a benefit that the high-wire trellising system provided was that fruit were easier to locate and harvest because they grew in one lower section of the main stem of each plant. In the modified-umbrella system, fruit were located on the main stem, secondary branches, or the "umbrella" branches and required harvesters to search for fruit in all areas of the plants. In addition, a stepladder was needed to harvest some fruit even though the study was conducted in a low-profile greenhouse with a top wire height of 2.1 m. These methods were common for hydroponic cucumber grown using the umbrella trellising system (Hao et al. 2007). The high-wire trellising system was developed, in part, in response to the increased construction of high-profile greenhouses with the ability to install top wires at higher heights (Welles 1999). This created a setting where plants are grown to taller heights, requiring elevated access by using scissor lifts, platforms, or other devices to train plants. Using a high-wire trellising system negates the need for elevated access during harvest because fruit are located at the lower part of the plant canopy. However, as noted, in Pennsylvania, most greenhouses are low profile.

In this study, we used identical and high plant densities of 4 plants/m^2 for both trellising systems. Hao et al. (2007) stated that for European cucumber, high plant densities of 2.2 to 4 plants/m^2 using the high-wire trellising system compared with 1.4 to 1.8 plants/m^2 for the umbrella system are needed for high yields with the high-wire system. When using equal plant densities for Beit Alpha cucumber, even when those densities were high, we observed marketable yields to be greater when using the modified-umbrella than the high-wire trellising system. For the high-wire system to have equal or higher productivity than a modified-umbrella system in a low-profile greenhouse, the high-wire system needs to be used with a higher plant population than the modified-umbrella system for Beit Alpha cucumber. In Pennsylvania, farmers growing Beit Alpha cucumber use plant densities of up to 6 to 8 plants/m^2 with a high-wire system. These plant densities are likely too high for the modified-umbrella system as they would interfere with draping the "umbrella" branches and result in an above optimal LAI.

Hydroponic Beit Alpha cucumber farmers using low (about 2 m) top wires or low-profile greenhouses can use a modified-umbrella or high-wire trellising system. Using the modified-umbrella trellising system will result in higher yields at equal plant densities (below 4 plants/m^2). However, the consistent weekly harvests we observed when using the high-wire trellising system may be preferred by farmers. In addition, in Pennsylvania, many farmers use plant densities higher than 4 plants/m^2 with the high-wire trellising system. This may increase LAI to above optimal levels, leading to lower per-plant yield and individual fruit weight. However, overall yields per unit area may be higher. Hao et al. (2010) reported that higher production costs due to increased plant numbers are a disadvantage of using high-wire trellising systems compared with a conventional umbrella system. Using twin-head plants in a high-wire trellising system with European cucumber resulted in equal and consistent yield and lower production costs than single-stem plants in a high-wire trellising system (Hao et al. 2010). This practice could have potential as an option for Beit Alpha cucumber farmers.

Conclusions and future research

Results showed that in a low-profile greenhouse, the modified-umbrella trellising system, commonly used for cucumber production, results in higher yields compared with the high-wire trellising system, an alternative plant training method recently growing in popularity. It was found that the modified-umbrella trellising system resulted in higher mean quantity and weight of harvested fruit compared with the high-wire trellising system. However, the increased yields obtained with the modified-umbrella trellising system were not distributed uniformly over the course of the growing season. The high-wire trellising system may produce a more consistent yield over time. This study evaluated these production methods under only one set of growing conditions and greenhouse dimensions. However, vegetable production can vary among growers, where vegetables can be produced under a variety of conditions and greenhouse dimensions. Although the results of this study show that the commonly used modified-umbrella system performs the best, there could be potential for further exploration of these systems. The modified-umbrella trellising system excels in yields at the planting density tested in this study. But there is potential for the high-wire trellising system to be effective by planting at higher densities than possible with the modified-umbrella trellising system. Another potential avenue for exploration is to evaluate the implementation of sequential planting using 3- to 4-week increments to obtain more consistent weekly yields with the modified-umbrella trellising system. Although the primary focus of this study was to determine the effect of the trellising system on yields, future research could also focus on other criteria farmers when selecting a cucumber training system, including labor requirements and production costs. Ultimately, deciding which trellising system is best to use depends on individual farmer goals and management preferences.

References cited

Bame M, Bullen SG. 2007. A cost assessment of growing greenhouse tomatoes in North Carolina. North Carolina State University Extension. https://vegetables.ces.ncsu.edu/wp-content/uploads/2018/04/GreenhouseTomatoSummary.pdf?fwd=no. [accessed 25 Mar 2024].

Ding L, Jiang Y, Yang S, Lizhong H, Zhou Q, Yu J, Huang D. 2020. Changes in leaf length, width, area, and photosynthesis of fruit cucumber in greenhouse production system. HortScience. 55:995–999. https://doi.org/10.21273/HORTSCI14637-19.

Fatnassi H, Boulard T, Benamara H, Roy JC, Suay R, Poncet C. 2017. Increasing the height and multiplying the number of spans of greenhouse: How far can we go? Acta Hortic. 1170:137–144. https://doi.org/10.17660/actahortic.2017.1170.15.

Hao X, Papadopoulos AP, Khosla S. 2007. Development of a high-wire cucumber production system on raised-troughs with supplemental lighting for year-round production. Acta Hortic. 761: 337–340. https://doi.org/10.17660/actahortic.2007.761.46.

Hao X, Papadopoulos AP. 1999. Effects of supplemental lighting and cover materials on growth, photosynthesis, biomass partitioning, early yield and quality of greenhouse cucumber. Scientia Hortic. 80:1–18. https://doi.org/10.1016/S0304-4238(98)00217-9.

Hao X, Wen G, Papadopoulos AP, Khosla SA. 2010. Twin-head "V" high-wire greenhouse cucumber production system for reducing crop start-up costs. HortTechnology. 20(6):963–970. https://doi.org/10.21273/HORTTECH.20.6.963.

Marcelis LM, Gijzen H. 1998. Evaluation under commercial conditions of a model of prediction of the yield and quality of cucumber fruits. Scientia Hortic. 76:171–181. https://doi.org/10.1016/S0304-4238(98)00156-3.

Papadopoulos AP. 1994. Growing greenhouse seedless cucumbers in soil and in soilless media. Agriculture and Agri-Food Canada Publication. Ottawa, Ontario, CA. https://doi.org/10.21273/hortsci.27.6.662c.

Porat R, Lichter A, Terry LA, Harker R, Buzby J. 2018. Postharvest losses of fruit and vegetables during retail and in consumers' homes: Quantification, causes, and means of prevention. Postharvest Biol Technol. 139:135–149. https://doi.org/10.1016/j.postharvbio.2017.11.019.

Produce Grower. US greenhouse production statistics released. 2016. Available online: https://www.producegrower.com/article/us-greenhouse-production-statistics-released. [accessed 19 Jul 2022].

Resh HM. 2013. Hydroponic food production: A definitive guidebook for the advanced home gardener and the commercial hydroponic grower (7th ed). CRC Press, Boca Raton, FL, USA. https://doi.org/10.1201/9781003133254.

Sharma N, Acharya S, Kumar K, Singh N, Chaurasia OP. 2018. Hydroponics as an advanced technique for vegetable production: An overview. J Soil Water Conserv. 17:364–371. https://doi.org/10.46676/ij-fanres.v4i2.143.

Shaw NL, Cantliffe DJ, Stoffella PJ. 2007. A new crop for North America greenhouse growers: Beit Alpha cucumber - progress of production technology through university research trials. Acta Hortic. 731: 251–258. https://doi.org/10.17660/actahortic.2007.731.34.

Shaw D, Cantliffe D, Rodriguez JC, Taylor SP, Spencer D. 2000. Beit Alpha cucumber - An exciting new greenhouse crop. Proceedings of the Annual Meeting of the Florida State Horticulture Society. 113:247–253. https://eurekamag.com/research/003/658/003658322.php.

Shaw NL, Cantliffe DJ, Funes Shine C III. 2004. Successful Beit Alpha cucumber production in the greenhouse using pine bark as an alternative soilless media. HortTechnology. 14:289–294. https://doi.org/10.21273/HORTTECH.14.2.0289.

US Department of Agriculture, National Agricultural Statistics Service. 2017. Census of Agriculture - Table 29. Vegetables, potatoes, and melons harvested for sale: 2017 and 2012. https://www.nass.usda.gov/Publications/AgCensus/2017/Full_Report/Volume_1,_Chapter_2_US_State_Level/st99_2_0029_0029.pdf. [accessed 4 Nov 2023].

US Department of Agriculture, National Agricultural Statistics Service. 2022. 2021–2022 Agricultural statistics annual bulletin - Pennsylvania. https://nass.usda.gov/Statistics_by_State/Pennsylvania/Publications/Annual_Statistical_Bulletin/2021-2022/2022_PA_Annual_Bulletin.pdf. [accessed 7 Nov 2023].

US Food and Drug Administration. 2020. Food loss and waste. https://www.fda.gov/food/consumers/food-loss-and-waste. [accessed 7 Nov 2023].

Von Zabeltitz C. 2011. Greenhouse structures, p 59–71. In: Integrated greenhouses systems for mild climates. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-14582-7_5.

Von Zabeltitz C. 2010. Design criteria for greenhouses, p 45–58. In: Integrated greenhouse systems for mild climates. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-14582-7_4.

Welles GWH. 1999. Fruit quality of glasshouse cucumber (*Cucumis sativus* L.) as influenced by cultural factors. Acta Hortic. 492:113–119. https://doi.org/10.17660/actahortic.1999.492.13.

Xiaolei S, Zhifeng W. 2004. The optimal leaf area index for cucumber photosynthesis and production in plastic greenhouse. Acta Hortic. 633:161–165. https://doi.org/10.17660/actahortic.2004.633.19.