Rootstock Evaluation for Grafted Cucumbers Grown in High Tunnels: Yield and Plant Growth

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Abstract. Grafting technology is increasingly being accepted in the United States, particularly for tomato (*Solanum lycopersicum*) production under protected structures. There is a great potential to expand this technology to other high tunnel crops. Using grafting technology in cucumber (*Cucumis sativus*) production is widely adopted in Asia to enhance cucumbers' tolerance to low temperatures. But this technique is rarely used in the United States mainly because of the lack of information on the performance of the grafted plants under local production systems. Figleaf gourd (*Cucurbita ficifolia*), *Cucurbita moschata*, and squash interspecific hybrid (*Cucurbita maxima* × *C. moschata*) are the most used cucumber rootstocks worldwide. But their comparative performance was largely unknown for cucumber production in high tunnels in the Midwest United States. This study was therefore designed to compare the major types of cucumber rootstocks with the goal of identifying a rootstock with the maximized benefits for high tunnel cucumber production in the area. Nongrafted 'Socrates' and 'Socrates' grafted with *Cucurbita moschata*, squash interspecific hybrid, and figleaf gourd rootstocks were evaluated in high tunnels from March to June or July in 2016–19 at the Southwest Purdue Agricultural Center in Vincennes, IN. Transplant establishment, vine growth, and yield in early- and main-crop seasons were investigated. Grafted plants regardless of rootstocks ensured transplant survival even when the soil temperatures were dropped below 10 °C. Suboptimal soil conditions were encountered in the first month after transplanting. Grafted cucumbers with squash interspecific hybrid rootstock significantly increased vine growth from March to April and increased early-season yields (yield before 15 May) by 1.8 to 18.2 times compared with the early-season yields of the nongrafted cucumbers. The benefits provided by using grafting technology dismissed around middle May. Only squash interspecific hybrid rootstock improved cucumber yields in the entire production seasons. Cucumbers grafted with figleaf gourd rootstock had the lowest yield and the least plant growth after mid-May, indicating figleaf gourd rootstock may not be suitable for cucumber production under the current production system. Overall, squash interspecific hybrid was the most promising rootstock for early-season high tunnel cucumber production in the Midwest United States.

Grafting is a cultural practice used on cucurbit and solanaceous crops for controlling soilborne diseases and improving plants' tolerance to abiotic stresses (Lee et al., 2010; Louws et al., 2010; Schwarz et al., 2010). Although the cost for grafted plants is two to five times more expensive compared with the normal transplants (Rivard et al., 2010), using grafted plants is steadily increasing in the United States (Grieneisen et al., 2018), particularly for tomato production under protected structures (Kubota, 2015; Singh et al., 2017). Studies have shown that regardless of the presence of soilborne diseases, grafting has the potential to increase high tunnel tomato yields (Meyer, 2016), and the high economic returns can generally compensate for the cost of using grafted plants (Rysin et al., 2015). Rapid adoption of high tunnels in the United States contributes to the in-

creased expansion of vegetable grafting technology (Louws et al., 2010). In addition to tomatoes, there is a great potential to expand the use of grafting technology to other high tunnel vegetables in the United States.

Cucumber is a high-value crop commonly grown in high tunnels (Lamont, 2009). As most high tunnels are not equipped with advanced environmental control systems in the United States (Carey et al., 2009), crops often suffer from low temperatures in the spring (Hunter et al., 2012). This is becoming a challenge for high tunnel cucumber production because this crop is highly sensitive to low-temperature stress.

Using grafting technology to strengthen cucumbers' tolerance to low temperatures is widely adopted in Asia (Davis et al., 2008). Although research for cucumber grafting was initially conducted for the purpose of con-

trolling fusarium wilt (*Fusarium oxysporum* Schlechtend:Fr f.sp. *cucumerinum* J.H. Owen) in the 1920s in Japan, cucumber grafting was not widely used until the 1960s, when it was recognized that grafting improves cucumbers' tolerance to low temperatures (Davis et al., 2008; Sakata et al., 2008).

Multiple species were found to be grafting compatible with cucumbers; they are *Cucurbita moschata*, *Cucurbita maxima*, figleaf gourd (*Cucurbita ficifolia*), squash interspecific hybrid (*C. maxima* × *C. moschata*), bottle gourd (*Lagenaria siceraria*), wax gourd (*Benincasa hispida*), luffa (*Luffa cylindrica*), burr cucumber (*Sicyos angulatus*), and melon (*Cucumis melo*) (King et al., 2010; Wang et al., 2004).

Cucurbita moschata and squash interspecific hybrid were the early developed cucumber rootstocks, but figleaf gourd was by far the most popular cucumber rootstock used in Asia because of its superior cold tolerance (King et al., 2010; Li et al., 2015). *Cucurbita* spp. rootstocks also provide grafted plants tolerance to fusarium wilt, phytophthora rot (*Phytophthora melonis* Katsura), and flooding conditions (Louws et al., 2010; Pavlou et al., 2002; Sakata et al., 2008; Wang et al., 2004). A unique feature for certain *Cucurbita moschata*-type rootstocks is the capability to produce "bloomingless" cucumber fruit. Such fruit has a distinct appearance and a longer shelf life, traits that are more favorable, especially in the Japanese market (Sakata et al., 2008). Burr cucumber has also been extensively evaluated as a cucumber rootstock because of its resistance to southern root-knot nematode [*Meloidogyne incognita* (Kofoid & White) Chitwood] (Gu et al., 2006; Zhang et al., 2006). However, poor and slow seed germination (Davis et al., 2008), as well as susceptibility to damping-off and gummy stem blight [*Didymella bryoniae* (Auersw.) Rehm] (Sakata et al., 2008) prevented the use of burr cucumber as a major cucumber rootstock.

Using grafted cucumber seedlings accounts for about 75% of the cucumber production in Japan and Korea (Lee et al., 2010) and nearly 100% of cucumbers grown in solar greenhouses in Northern China (Huang et al., 2015). Figleaf gourd, *Cucurbita moschata*, and squash interspecific hybrid are the most used rootstocks (Huang et al., 2015). In general, figleaf gourd was used as a rootstock for winter cucumber production, and squash interspecific hybrid and *C. moschata* rootstocks are more commonly used for summer cucumber production in Japan (Sakata et al., 2008).

Although using grafted cucumber plants is a routine practice in Asia, this technique is rarely used in the United States mainly because of the lack of information on the performance of the grafted plants under local production systems. In the Midwest United States, cucumber production primarily happens in the summer months, although high tunnels have extended the production season into spring. This is different from the solar

greenhouse system, which allows cucumber production throughout the winter in northern China (Wang et al., 2009). In our previous research, we found grafting cucumbers with *C. moschata* rootstock can enhance early-season high tunnel cucumber production, but results were inconsistent when cucumber production extended into the summer (Guan et al., 2018). As only one rootstock was evaluated, the previous study may not exhibit the full potential of using grafting technology in high tunnel cucumber production. The current research was therefore designed to compare the major types of cucumber rootstocks with the goal of identifying a rootstock with the maximized benefits for high tunnel cucumber production in the Midwest United States.

Materials and Methods

Plant materials. The study was conducted during 2016–19 at the Southwest Purdue Agricultural Center (SWPAC), Vincennes, IN (USDA hardiness zone 6). A beita-type cucumber, ‘Socrates’ (Johnny’s Selected Seeds, Winslow, ME), was used as the scion and nongrafted controls for all four years.

Rootstock type, scientific name, cultivar name, and seed source of rootstocks used in the four seasons are provided in Table 1. Squash interspecific hybrid and *Cucurbita moschata* rootstocks were evaluated in 2016–19; figleaf gourd was evaluated in 2018 and 2019. Squash interspecific hybrid cultivar Cobalt was used in 2017–19, while cultivar RST-04-109-W was used in 2016.

Cucumber grafting and transplant production. Rootstock and scion seeds were sown in 50-cell trays filled with a peat-based growing mix (Sungro Horticulture, Agawam, MA) in all four seasons. Rootstock seeds were planted on 20 Feb., and scion seeds were planted 1 or 2 d later. Grafting was performed about a week later after the scion seeds were planted, at the time when both

rootstock and scion plants had the first true leaf just emerge. All the plants were grafted with the hole-insertion grafting method in 2016. The one-cotyledon method was used in 2017–19, except for figleaf gourd rootstock. Figleaf gourd rootstock had a short hypocotyl that prevented grafting from using the one-cotyledon method. The hole-insertion method was then used on figleaf gourd rootstock in both 2018 and 2019. A detailed grafting procedure for both one-cotyledon and hole-insertion grafting methods can be found in Guan and Zhao (2015). Briefly, for the hole-insertion method, the hypocotyl of a cucumber scion was inserted into a hole made at the apical meristem tissue of a rootstock plant. For the one-cotyledon method, the scion plant was cut at the hypocotyl and attached to a rootstock plant that has had one of the cotyledons and the apical meristem tissue removed.

Grafted plants were healed in a healing chamber that was built with PVC pipe frame and plastic film cover in 2016 on a greenhouse bench (Guan et al., 2018). From 2017 to 2019, grafted plants were healed in a growth chamber and covered with a plastic film (Guan, 2019). The newly grafted plants were exposed to the environment with 100% relative humidity and temperatures ranging from 25 to 30 °C. Relative humidity was gradually reduced during the graft healing period, which lasted about 7 d. Nongrafted cucumbers were exposed to similar environmental conditions as the grafted plants. Above 90% survival rates were achieved in all four seasons, regardless of the rootstocks. Grafted and nongrafted plants were grown in a greenhouse at SWPAC for about 2 weeks after graft healing until they were ready to be transplanted in high tunnels.

High tunnel cucumber production. The high tunnels (Rimol Greenhouse Systems, Inc., Hooksett, NH) at SWPAC are gothic-style tunnels that are 30 ft wide and 96 ft long. They are equipped with ridge vents that opened when temperatures reached 24 °C and closed when temperatures dropped below 15 °C. The side walls were opened when temperatures were above 27 °C.

Initial transplant dates and the replant dates for all four seasons are presented in Table 2. Seedlings were planted on beds covered with black-plastic mulch, with one drip tape having an 8-inch emitter spacing in the middle of each bed. The in-row plant spacing was 0.3 m. Row cover (50.8 g/m², GR-RC15; GreenhouseMegastore Inc., Los Angeles, CA) was used for frost protection when the lowest air temperatures outside of the high tunnel were below 0 °C. The row covers were placed on wired hoops that were installed every 1.5 m.

Plants were trellised to a single leader system. Suckers as well as lower leaves of each vine were pruned every week in 2016–18 and biweekly in 2019. After the lower leaves were pruned, vines were dropped to the ground. Plants were maintained at around a 1.5 m height with about 15 fully expanded newer leaves.

Urea (46N–0P–0K) at 33.6 kg/ha nitrogen (N) was incorporated in the soil before planting. Micronutrients were also applied pre-plant, according to soil test results. Plants were fertigated three times per day, beginning 2 weeks after transplanting, with potassium nitrate [13.7N–0P–38.5K (Krista K; Yara International, Oslo, Norway)] and with urea ammonium nitrate solution [28N–0P–0K (CF Industries Holdings, Inc., Deerfield, IL)] at a rate of 1.12 kg/ha N per day. Throughout the season, soil moisture was maintained around field capacity. The average volumetric water content was about 0.2 m³·m⁻³ at a soil depth of 15 cm. Depending on the presence of insect pests, bifenthrin (Acramite 50 WS; Chemtura Corporation, Middlebury, CT) and potassium salts of fatty acids (M-Pede; Dow AgroSciences, Indianapolis, IN) were used to control two-spotted spider mites (*Tetranychus urticae*). Imidacloprid (Admire Pro; Bayer CropScience LP, Research Triangle Park, NC) was used to control cucumber beetles (*Acalymma vittatum* and *Diabrotica undecimpunctata*).

Data collection. Cucumbers were harvested three times per week at about a 17–20 cm length. Cucumbers that were misshaped and had scars were separated from the marketable fruit. Yield by weight and fruit number were recorded. The same harvest and grading standard were used for all the treatments. Harvest durations in each crop season are presented in Table 2. Plant vine lengths, measured from soil-line to the tip of the growing point of each plant, were recorded around 20 Apr., and then in the middle of the following months of each crop season. Data loggers (Pro V2; Onset, Bourne, MA) were placed in the center of the high tunnels; these automatically recorded air and soil temperatures at 30 min in 2017–19. Air temperatures were recorded at the height of plant canopies, and soil temperatures were recorded with external sensors placed about a 10 cm depth. The data logger was first set at about a 0.5 m height and then gradually moved to a 1.5 m height and stayed in the position till the end of the season.

Experimental design and statistical analyses. Randomized complete block designs were used in each of the four seasons. Four blocks were used in 2018, while three blocks were used in the other seasons. Each block included five plants.

Main effects of season, grafting, and their interactions on early-season yield (yield before 15 May), main-season yield (yield after 15 May), and total yield were analyzed using PROC MIXED procedure SAS 9.4 (SAS Institute Inc., Cary, NC). Plant growth was analyzed for each season separately. Normality, homogeneity of variances, and linearity were tested. Tukey’s honestly significant difference test was used for multiple comparisons among different treatments ($\alpha = 0.05$).

Results and Discussion

Transplant establishment. Transplant establishment rate was 100% on grafted plants in all the four seasons, irrespective of the

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rootstocks. Transplant failure within 10 d post planting was observed on nongrafted plants in three of the four seasons (2016, 2018, and 2019). Replant rates for the nongrafted plants were 44.4%, 91.7%, and 77.7% in 2016, 2018, and 2019, respectively (Table 2).

The daily average and minimal soil and air temperatures from 20–30 Mar. in 2017–19 are presented in Fig. 1. Plants encountered the lowest average soil temperatures after transplanting in 2018. Daily average soil temperatures dropped to 10.8 °C 2 d after transplanting, with the recorded minimal soil

temperature at 8.4 °C. On 24 Mar. 2018, plants were exposed to a lower than 10 °C soil temperature condition for at least 16 h. Correspondingly, above 90% of nongrafted cucumbers died in 2018.

Wilting was first observed on the unsuccessfully established plants; that agreed with

Table 1. Rootstock type, scientific name, cultivar name, and seed source of rootstocks evaluated in the 2016–19 production seasons in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN.

Rootstock type	Scientific name	Cultivar name	Seed source
Squash interspecific hybrid	<i>Cucurbita maxima</i> × <i>Cucurbita moschata</i>	Cobalt	Rijk Zwaan, Fijnaart, Netherlands
Squash interspecific hybrid	<i>C. maxima</i> × <i>C. moschata</i>	RST-04-109-W	DP Seeds LLC, Yuma, AZ
<i>C. moschata</i>	<i>C. moschata</i>	Marvel	American Takii, Salinas, CA
Fingleaf gourd	<i>Cucurbita ficifolia</i>	White Skin	Known-You Seed Co., Kaohsiung, Taiwan

Table 2. Initial transplant date, replant date, percentages of replanted nongrafted plants, and the harvest duration in the 2016–19 production seasons in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN.

Season	Initial transplant date	Replant date	Percentages of replanted nongrafted plants ^z	Harvest duration
2016	30 Mar.	9 Apr.	44.4%	4 May–31 July
2017	20 Mar.	NA ^y	0%	13 Apr.–26 June
2018	22 Mar.	10 Apr.	91.7%	25 Apr.–30 July
2019	20 Mar.	27 Mar.	77.7%	24 Apr.–1 July

^zNo grafted plants were replanted in the four seasons, irrespective of the rootstocks.

^yNA = not available. All the plants survived in 2017. No plants were replanted.

Fig. 1. The daily average and minimal soil and air temperatures (°C) exposed by the grafted and nongrafted cucumber plants in 20–30 Mar. in 2017–19 in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN.

the previous claim that the most common visible symptom of exposing root system to a low temperature is the dehydration of leaves (Lee et al., 2004b). Lee et al. (2004a) found cucumber root pressure that measures roots' ability to absorb water was dropped to 0 MPa when cucumber roots were exposed to 8 °C, indicating the nongrafted cucumber plants were exposed to a lethal low-temperature condition in 2018.

All the cucumber seedlings survived in 2017 when the daily average soil temperatures during the first 10 d after transplanting ranged from 15.3 to 18.2 °C. However, it is worth noting that cucumber transplant failure could happen when soil temperatures were between 14 and 16 °C (Den Nijs, 1980). Factors such as light conditions, plant water, nutritional status, and cultivars determine the chance of plant survival at the threshold temperature conditions (Pellett and Carter, 1981).

One hundred percent survival rate of the grafted cucumbers was achieved in all the four seasons, which was consistent with the previous observation made by Den Nijs (1980). Although figleaf gourd is known to be more tolerant to the low temperature stress compared with the other rootstocks (King et al., 2010), difference in seedling survival among the different rootstocks was not observed under the current conditions.

Interestingly, the recorded minimal air temperatures were below 0 °C after planting in both 2018 and 2019. The below-freezing temperatures lasted 4–5 h, but they did not result in the death of any grafted plants. Mechanisms of the improved cold tolerance of grafted plants with figleaf gourd rootstock have been investigated. Horváth et al. (1983) found an increased level of *trans*-hexadecenoic acid in phosphatidyl glycerol of leaves of the grafted plants, suggesting the rootstock affects the phospholipid composition of the scion leaves. Horváth et al. (1982) found rootstock-influenced lipid phase separation of phospholipid fraction of the scion leaves. Studies also indicated that the rootstock stimulated the antioxidative defense system of the scion (Li et al., 2015).

Vine growth and crop yield. Vine growth in the four production seasons is presented in Fig. 2. From transplanting to around 20 Apr., squash interspecific hybrid and figleaf gourd rootstock-grafted cucumbers consistently had greater vine length compared with that of nongrafted cucumbers. Significant differences between *C. moschata* rootstock-grafted cucumbers and the nongrafted cucumbers were detected in 2017 and 2018, but not in 2016 and 2019. The difference in the vine growth among nongrafted and grafted cucumbers was less pronounced in the second months (April to May) of the crop seasons. In the third month (May to June), the least plant

growth was observed on figleaf gourd rootstock-grafted cucumbers, which was significantly less compared with that of the squash interspecific hybrid rootstock-grafted cucumbers in both 2018 and 2019. Nongrafted cucumbers had similar plant growth compared with the grafted plants in the third (2016–19) and the fourth months (2016 and 2018).

Average soil temperatures before 10 Apr. rarely reached 20 °C (Fig. 3). Tachibana (1987) reported that water and nutrient absorption rate of cucumber plants were greatly inhibited when the plants were preincubated at root temperatures below 20 °C for 1 or 5 d. Cucumber plants' dry weight, leaf area, and net photosynthesis were seriously impacted when root temperatures were below 20 °C (Ahn et al., 1999). The low temperature effects, however, were not observed on cucumbers grafted on figleaf gourd rootstock (Ahn et al., 1999), which supported our observations that nongrafted cucumbers had shorter vine length compared with figleaf gourd rootstock-grafted cucumbers in the early period of the crop seasons. Although figleaf gourd rootstock was known to be more tolerant to cold (King et al., 2010), recently developed squash rootstocks also showed outstanding cold tolerance (Li et al., 2015). In the current evaluations (2018 and 2019), figleaf gourd rootstock-grafted cucumbers had numerically longer vine length in the

Fig. 2. Vine growth (cm) of grafted and nongrafted cucumbers grown in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN during each month in the 2016–19 production seasons. Vine growth in the first month was measured on 22 Apr. 2016, 19 Apr. 2017, 24 Apr. 2018, and 22 Apr. 2019. Vine growth in the following months was calculated by subtracting vine length measured in the middle of each month from measurements in the previous months for each production season. Treatment analyses were separated by month. Means for each month having the same letter were not significantly different by Tukey's honestly significant difference test ($\alpha = 0.05$).

early period of the crop seasons but the values were not significantly different from the other rootstock-grafted cucumbers (Fig. 2).

Soil temperatures stayed above 20 °C after mid-May, which was optimal for cucumber growth. Grafted cucumber plants did not show an advantage for plant growth in the third and the fourth months in the crop seasons. Interestingly, vines of figleaf gourd rootstock-grafted cucumbers grew the least, compared with the other treatments. Zhang et al. (2008) reported that when soil temperature was at 24 °C, plant dry mass, net photosynthesis, and stomatal conductance of cucumber were higher than those of figleaf gourd itself, suggesting the growth of the

figleaf gourd plants may be inhibited by temperatures that were optimal for cucumber growth.

Consistent among the four seasons, grafted cucumbers had significantly greater early-season yields (yield prior to 15 May) compared with that of nongrafted cucumbers (Table 3). The only exception was in 2019, when early-season yield of *C. moschata* rootstock-grafted cucumbers was like that of nongrafted cucumbers. In 2017, when there was no replant for the nongrafted plants after transplanting on 20 Mar., early-season yield of grafted cucumbers was 2.65 times higher than the early-season yield of nongrafted plants. The most dramatic difference in early-season yields between

grafted and nongrafted plants was observed in 2018, when above 90% of the nongrafted plants were replanted on 10 Apr. after initial transplanting on 22 Mar. Early-season yield of grafted plants was close to 20 times more than the yield of nongrafted plants in 2018. The different levels of early-season yield benefits provided by the grafted plants under the different circumstances may contribute to the season and grafting treatment interaction for the early-season yields (Table 4).

No season and grafting treatment interactions were detected for the main-season yield (yield after 15 May) and the total yield (yield for the entire seasons); thus the data among the four seasons were presented together

Fig. 3. Average soil temperatures (°C) in the production seasons of 2017–19 in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN.

Table 3. Early-season yields (yield before 15 May) of nongrafted cucumbers, and grafted cucumbers with *Cucurbita moschata*, squash interspecific hybrid (*Cucurbita maxima* × *C. moschata*), and figleaf gourd (*Cucurbita ficifolia*) rootstocks grown in high tunnels in the 2016–19 production seasons at the Southwest Purdue Agricultural Center, Vincennes, IN.

Grafting treatment	2016 (kg/plant)	2017 (kg/plant)	2018 (kg/plant)	2019 (kg/plant)
Nongrafted cucumber ‘Socrates’	0.15 b ^y	0.70 b	0.04 b	0.64 b
‘Socrates’ grafted with <i>C. moschata</i> rootstock ‘Marvel’	0.57 a	1.82 a	0.77 a	0.86 ab
‘Socrates’ grafted with squash interspecific hybrid rootstock ‘Cobalt’ or ‘RST-04-109-W’	0.64 a	1.88 a	0.73 a	1.18 a
‘Socrates’ grafted with figleaf gourd rootstock ‘White Skin’	NA ^z	NA	0.87 a	1.10 a

^zNA = not available. Grafted cucumber with figleaf gourd rootstock was not evaluated in 2016 and 2017.

^yMeans within a column followed by the same letter were not significantly different by Tukey’s honestly significant difference test ($\alpha = 0.05$).

Table 4. Effects of production season and grafting treatment on early-season, main-season, and total yields of the cucumbers grown in the 2016–19 production seasons in high tunnels at the Southwest Purdue Agricultural Center, Vincennes, IN.

Factor	Early-season yield ^z	Main-season yield ^y	Total yield
Season	0.0008	<0.0001	0.0001
Grafting treatment	<0.0001	0.0041	0.0019
Season × grafting treatment	<0.0001	0.1653	0.1171

^zEarly-season yield was defined as yield before 15 May.

^yMain-season yield was defined as yield after 15 May.

Table 5. Main-season (yield after 15 May) and total (yield for the entire seasons) yields of nongrafted cucumbers, and grafted cucumbers with *Cucurbita moschata*, squash interspecific hybrid (*Cucurbita maxima* × *C. moschata*), and figleaf gourd (*Cucurbita ficifolia*) rootstocks grown in high tunnels in the 2016–19 production seasons at the Southwest Purdue Agricultural Center, Vincennes, IN.

Grafting treatment	Main-season yield (kg/plant)	Total yield (kg/plant)
Nongrafted cucumber ‘Socrates’	7.96 ab ^z	8.32 b
‘Socrates’ grafted with <i>C. moschata</i> rootstock ‘Marvel’	7.98 ab	8.97 ab
‘Socrates’ grafted with squash interspecific hybrid rootstock ‘Cobalt’ or ‘RST-04-109-W’	9.32 a	10.41 a
‘Socrates’ grafted with figleaf gourd rootstock ‘White Skin’	6.80 b	7.77 b

^zMeans within a column followed by the same letter were not significantly different by Tukey’s honestly significant difference test ($\alpha = 0.05$).

(Table 5). Nongrafted cucumbers had similar main-season yield compared with that of grafted cucumbers, regardless of the rootstocks. Significant difference for the total yield occurred between nongrafted plants and grafted plants with the squash interspecific hybrid rootstock, but not on the other rootstock-grafted cucumbers. Similar results were reported in cucumbers grown in greenhouse soilless culture (Maršić and Jakše, 2010). Comparing among rootstocks, grafted plants with squash interspecific hybrid rootstock had significantly higher main-season and total yields compared with that of figleaf gourd rootstock-grafted cucumbers, a result that agreed with our observations that growth of figleaf gourd rootstock-grafted cucumbers was suppressed in the later half of the growing seasons.

Conclusions

This study supported previous observations that grafting can be a valuable tool for enhancing early-season high tunnel cucumber production in the Midwest United States. Regardless of the rootstocks, grafted plants ensured transplant survival, even when soil temperatures dropped below 10 °C, which is not unusual in the early spring when warm-season vegetables are ready to be transplanted in the high tunnels. In the first month after transplanting, with soil temperatures below 20 °C, grafted cucumbers with all the evaluated rootstocks can significantly improve plant growth. It is possible to harvest up to 1.88 kg of cucumbers per plant before 15 May in an unheated high tunnel in the USDA hardiness zone 6 by using grafted plants with squash interspecific hybrid rootstock. Considering the premium price farmers may receive for early-season cucumbers, grafting technology may be economically valuable for high tunnel cucumber production. Economic analyses are warranted to approve the assumption.

The benefits provided by using grafting technology dismissed after mid-May when soil temperatures stayed above 20 °C. Only squash interspecific hybrid rootstock-grafted cucumbers improved yields of the entire crop seasons in the current study.

Although figleaf gourd was known to be the most cold-tolerant rootstock, figleaf gourd did not show superior performance compared with the squash rootstocks in the early seasons under the current conditions. Furthermore, grafted cucumbers with figleaf gourd rootstock had the lowest yield and the least plant growth during the main seasons, indicating figleaf gourd rootstock may not be suitable for cucumber production under the current production system. Overall, considering the yield and plant growth benefits provided by the squash interspecific hybrid rootstock, it was the most promising rootstock for high tunnel cucumber production in the Midwest United States.

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