HortScience 57(10):1267–1277. 2022. https://doi.org/10.21273/HORTSCI16553-22

Grape Tomato Growth, Yield, and Fruit Mineral Content as Affected by Rootstocks in a High Tunnel Organic Production System

Tian Gong
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611

Xuelian Zhang
College of Life Sciences, South China Agricultural University, Guangzhou, 510642, China

Jeffrey K. Brecht, Zachary E. Black, and Xin Zhao
Horticultural Sciences Department, University of Florida, Gainesville, FL 32611

Additional index words. determinate scion, generative rootstock, indeterminate scion, root-knot nematode, rootstock-scion synergy, *Solanum lycopersicum*, vegetative rootstock

Abstract. **Recently, so-called "vegetative" and "generative" rootstocks have been identified by seed companies as rootstock types that have different impacts on tomato scions. In this experiment of grafted grape tomato production in an organically managed high tunnel system, we characterized the effects of vegetative and generative rootstock cultivars on tomato yield components and fruit mineral contents. Grape tomato scions 'BHN 1022' (determinate) and 'Sweet Hearts' (indeterminate) were grafted onto 'DR0141TX' (vegetative), 'Estamino' (generative), and 'Multifort' (noncharacterized) rootstocks with self- and nongrafted scions as controls. Experiments were conducted twice with different transplanting dates (Expt. 1: 31 Jan. vs. Expt. 2: 9 Mar.) in 2018. No rootstock by scion interaction effects on whole-season fruit yield components were observed, indicating similar responses of determinate and indeterminate grape tomato scions to all rootstocks tested. For Expt. 1, the three rootstocks increased marketable fruit number, marketable yield, and total yield by 23.3%, 37.9%, and 34.4% on average, respectively, compared with the self- and nongrafted controls, primarily due to improved productivity during the peak and late harvest periods. For Expt. 2, the rootstocks did not significantly benefit any whole-season yield components. 'DR0141TX' and 'Multifort' increased stem diameter in both experiments, whereas 'Estamino' only increased stem diameter in Expt. 2 relative to the nongrafted controls. Consistent increase in aboveground dry biomass of rootstock treatments at crop termination in Expt. 1 corresponded to the greater yield of rootstock-grafted plants in that experiment. All rootstocks in both experiments consistently increased fruit P, K, Ca, Zn, and Fe contents on a dry weight basis at peak harvest regardless of the tomato scion used. Despite a relatively low level of root-knot nematode infestation, plants grafted with 'DR0141TX' or 'Estamino' tended to have lower root galling index ratings than scion controls and 'Multifort'-grafted plants, which was more evident in Expt. 1. Given the different environmental conditions during the tomato production period between the two experiments conducted in high tunnels, our findings highlight the important influence of production environment on grafted tomato performance. This study on grafted grape tomatoes in high tunnel organic production systems also demonstrated that so-called "vegetative" and "generative" rootstocks had similar impacts on tomato scion yield components and fruit mineral contents.**

Tomato (*Solanum lycopersicum*) production has increased globally in the past 5 decades (Costa and Heuvelink, 2018). Grafting is a technique that combines plants from the same genus or family to form a new plant with desirable traits (Melnyk, 2017). Grower interest in using grafted plants in tomato production is rapidly growing around the world, most recently in the United States. Rootstock cultivars available for tomato grafting have been reported to improve many features of the grafted plants, including resistance to soilborne pathogens and tolerance to abiotic stresses (Rivard and Louws, 2008; Suchoff et al., 2018b), nutrient uptake (Djidonou et al., 2015), water use efficiency, and fruit yields (Djidonou et al., 2013; Suchoff et al., 2018a). The widespread cultivation and economic benefit of tomato have stimulated the development and improvement of tomato rootstocks. Numerous rootstocks have been introduced into the U.S. market, with the number of cultivars having increased nearly 10-fold within the 6 years before 2015 (Hu et al., 2015). Rootstocks have been mainly characterized by seed companies according to their resistances to fungal and bacterial pathogens and root-knot nematodes since disease management has been a key driving factor for tomato grafting adoption by producers.

Recently, some seed companies have begun to use the terms "vegetative" and "generative" to describe the effects of certain rootstocks on tomato scions. Lopez-Marin et al. (2017) suggested that vigorous vegetative rootstocks were more suitable for large-fruited tomato cultivars grown in long cropping cycles, and generative rootstocks were better for small-fruited cultivars grown in any cropping cycles or for large-fruited cultivars in short cropping cycles. However, scientific evidence is absent for discerning the fundamental characteristics of so-called "vegetative" and "generative" rootstocks in grafting different scion genotypes. When using grafted plants, adverse rootstock-scion interactions could lead to loss of fruit quality, reduced yield, and shortened shelf life (Gaion et al., 2018). Research is thus needed to obtain a comprehensive understanding of vegetative and generative rootstocks to optimize rootstock-scion synergy.

Tomato cultivars can be generally classified as determinate, semideterminate, and indeterminate according to their growth habit, which can be distinguished by shoot development (Vicente et al., 2015; Wang et al., 2009). For determinate tomato cultivars, the first part of the growing season is characterized by the vegetative phase, and the latter part of the growing season is driven by the reproductive phase. In contrast, for indeterminate tomato cultivars, although the vegetative phase also dominates during the first period of the growing season, there is a relatively equal balance of vegetative and reproductive activity during the second period of the growing season. Thus, during the latter part of the growing season, indeterminate tomato plants continuously produce flowers and fruit (Vicente et al., 2015). Determinate and indeterminate types exist in both beefsteak tomato and grape tomato cultivars, whereas no information is available for comparing the rootstock effects on growth and development of determinate and indeterminate grape tomatoes.

Minerals serve important physiological functions in plant growth and development and their contents expressed on a dry weight basis are indices of plant nutrient status and are commonly used for plant health diagnosis (Hochmuth, 2018). Mineral contents on a dry weight basis in fruit could be indicators of plant mineral accumulation and partitioning. Previous studies have examined the influence of rootstocks on the mineral nutrient status of grafted tomato plants, either at the whole plant level (Leonardi and Giuffrida, 2006) or at the leaf level (Borgognone et al., 2013; Goto et al., 2013) under normal or stressed conditions (Kumar et al., 2015; Sánchez-Rodríguez et al., 2014; Savvas et al., 2011). Yet, few studies have been conducted to characterize rootstock effects on tomato fruit mineral composition

(Riga et al., 2016). Minerals also constitute an important part of the health benefits of tomatoes (Bertin and Génard, 2018). In this case, expressing mineral contents in fruit on a fresh weight basis better represents the nutritive value, as fruit from grafted and nongrafted plants can have different dry matter contents as reported by previous researchers (Djidonou et al., 2016; Turhan et al., 2011). However, fruit mineral contents reported on a fresh weight basis is scarce.

In this study, we used three rootstocks with different characteristics, including so-called vegetative and generative rootstocks, grafting them with determinate vs. indeterminate grape tomato cultivars, to assess plant growth, yield components, and fruit mineral nutrient status under high tunnel organic production. The objectives were to 1) determine effects of these rootstocks with putative differences in vegetative and generative impacts on grape tomato scion performance, and 2) characterize the responses of determinate and indeterminate grape tomato scions to grafting.

Materials and Methods

Experimental material. Two experiments with different tomato transplanting dates were carried out in 2018. In both experiments, determinate grape tomato 'BHN 1022' (Siegers Seed Co., Moultrie, GA) and indeterminate grape tomato 'Sweet Hearts' (Sakata Seed America, Morgan Hill, CA) seedlings were grafted onto the following tomato rootstocks: 'DR0141TX' (De Ruiter Seeds, Bergschenhoek, the Netherlands), 'Estamino' (Vitalis Organic Seed, Salinas, CA), and 'Multifort' (De Ruiter Seeds). 'DR0141TX' and 'Estamino' have been claimed by some seed companies as "vegetative" and "generative" rootstocks, respectively, and all three rootstocks are described as being vigorous. Self- and nongrafted tomato scions were used as controls.

Tomato rootstocks and scions were seeded on 27 Nov. 2017 for Expt. 1, and rootstocks and scions were seeded on 22 and 25 Jan. 2018, respectively, for Expt. 2. Seeds were sown in 72-cell Speedling trays (Speedling Inc., Ruskin, FL) filled with organic media (Fafard Natural & Organic Potting Mix; Fafard, Agawam, MA). After the emergence of the first true leaf, plants were fertilized every 4 d with a nutrient solution containing 2N–1.3P–0.8K fish and seaweed organic fertilizer (Neptune's Harvest, Gloucester, MA) and 0N–0P–41.5K potassium sulfate (Big K, allowed for organic production; JH Biotech, Inc., Ventura, CA) with N and K concentrations of 200 and 166 mg/L, respectively.

Plants with three to four true leaves were grafted using the splice grafting method (Djidonou et al., 2013) on 4 Jan. (38 d after rootstock seeding) and 23 Feb. 2018 (32 d after rootstock seeding) for Expt. 1 and Expt. 2, respectively. Seedlings were cut below the cotyledons of the rootstock to prevent rootstock suckering, and scions were cut between the cotyledons and the first true leaf to match the rootstock stem diameter. The grafted seedlings were then placed in a healing chamber at 25 °C and ≈95% relative humidity (RH) with fluorescent light (photosynthetic photon flux density 64 μmol/s/m^2) and 12 h photoperiod. Humidity was gradually reduced from 4 d after grafting (DAG) and the plants were transported to a research greenhouse on the University of Florida campus (Gainesville, FL) at 8 DAG for acclimation before field transplanting. All seedlings including grafted plants and self- and nongrafted scions were then fertilized following the same protocol used before grafting. Plants in the greenhouse were hand watered every 1 to 2 d during the transplant production process.

Setup of the high tunnel grafted tomato experiment. The grafted organic tomato production experiment was conducted in Spring 2018 in a three-bay high tunnel on certified organic land at the University of Florida Plant Science Research and Education Unit in Citra, FL. Each high tunnel bay was 25.60 m long, 9.14 m wide, and 3.05 m high with bow spacing at 1.83 m. The three-bay high tunnel roof was covered by double-layer polyethylene plastic film (6 mil) with air inflation, and roll-up weave fabric curtains were installed for sidewalls and endwalls. Planting beds were arranged in the north to south orientation. The texture of the soil was 95.2% sand, 3.1% silt, and 1.7% clay with 0.78% organic matter. A randomized complete block design was used with four replications and five plants per plot. Plants for Expt. 1 were transplanted on 31 Jan., which was ≈1 to 1.5 months earlier than the normal transplanting for open field tomato production in north Florida. Plants for Expt. 2 were transplanted on 9 Mar., which was similar to the normal transplanting time for open field tomato production in the area. Plants were transplanted into raised beds that were 15 cm high and 95 cm wide with black plastic mulch and drip irrigation. The between-bed (center to center) spacing was 1.83 m and plant spacing within each bed was 0.46 m. Single-line drip tape was used with 15 cm emitter spacing and a flow rate of 1.9 L/min per 30.5 m (Jain Irrigation Systems Ltd., Bambhori, India). Irrigation was set to run for 20 min at each event and the frequency was increased from two to four times per day as the season progressed and the average daily temperatures increased.

Cow manure–based compost (Black Kow; Black Gold Compost Company, Oxford, FL) was applied at a rate of 22.4 t·ha^{-1}, and Nature Safe 10N–0.9P–6.6K organic fertilizer (Darling Ingredients Inc., Irving, TX) was applied preplant at a rate of 2242 kg·ha^{-1}, that is, 224.0, 20.2, and 148.0 kg per ha for N, P, and K, respectively. During the production season, supplemental fertilizer was provided by applying weekly injections of 5N–0.4P–0.8K liquid fish fertilizer (Aqua Power 5–1–1; JH Biotech, Inc.) and 0N–0P–41.5K potassium sulfate (Big K, JH Biotech, Inc.) at the combined rate of 10.4 kg·ha^{-1} N and 13.0 kg·ha^{-1} K per week from 3 until 18 weeks after transplanting (WAT) for Expt. 1 and from 5 until 15 WAT for Expt. 2. Potassium rate was increased to 26.1 kg·ha^{-1} per week from 7 to 9 WAT in Expt. 1 and 19.5 kg·ha^{-1} per week for 12 and 13 WAT in Expt. 1, and 9 and 10 WAT in Expt. 2. The weekly N application rate during the production season was also adjusted to 7.8 or 15.7 kg·ha^{-1} as needed based on the crop stage. For Expt. 1, $MgSO_4$ (Epsom salt) was foliar applied at a rate of 1.12 kg·ha^{-1} on 20 Mar., 28 Mar., and 6 Apr., and at a concentration of 2.24 kg·ha^{-1} on 4 May. For Expt. 2, $MgSO_4$ was foliar applied at 2.24 kg·ha^{-1} on 4 May. For both experiments, 1N–0P–0K-3B (BIOMIN BOOSTER 126; JH Biotech, Inc.) was foliar applied at 1.68 kg·ha^{-1} on 4 May. For each foliar application, ≈187 L of water was sprayed per ha. White light–diffusing shadecloth (HARMONY 3915 O E; Ludvig Svensson, Inc., Charlotte, NC) was put up to cover the high tunnel roof on 12 June.

Plants were trellised onto a vertical net (Hortonova LM; Tenax Corp., Baltimore, MD), and fastened with a Tapener plant tying tool (HT-R2; MAX Co. Ltd., Tokyo, Japan). Lateral branches were pruned to the first inflorescence on 'BHN 1022', and 'Sweet Hearts' branches were pruned to the second inflorescence. Leaves that were touching the ground, senescent, or severely affected by pests or diseases were pruned once per week during early harvest for both experiments to increase airflow and reduce disease pressure. Organic fungicides and insecticides were applied for disease and pest management according to an IPM program established for the research trials. During the tomato production season (from 1 Feb. to 16 July), air temperature and RH at 1 m above the planting bed in the middle of the high tunnel were recorded every 15 min using HOBO data loggers (Model H08-002-02; Onset Computer Corporation, Bourne, MA).

Fruit yield components. Tomato harvests began on 23 Mar. [51 d after transplanting (DAT)] and 11 May (63 DAT) for Expts. 1 and 2, respectively. Fruit were generally harvested twice per week when they reached a uniform, complete red color with a tinge of orange. Harvested fruit were classified as either marketable or unmarketable and were weighed and counted. Fruit were considered unmarketable if weighing <5 g, or with more than 30% stink bug damage over the surface, cracking, or damage by other pests, or showing any disease symptoms. Fruit were counted and weighed at each harvest. Average marketable fruit weight was calculated by dividing marketable yield by marketable

Received for publication 18 Feb. 2022. Accepted for publication 19 May 2022.

Published online 29 August 2022.

This work was supported by Specialty Crop Research Initiative grant no. 2016-51181-25404 and Organic Agriculture Research and Extension Initiative grant no. 2017-51300-26813 from the U.S. Department of Agriculture National Institute of Food and Agriculture. Dr. Xuelian Zhang was also awarded a fellowship from the China Scholarship Council during 2017–2018 for her participation in the research project. We thank James Colee for his assistance with the statistical analysis.

X. Zhao is the corresponding author. E-mail: zxin@ufl.edu.

fruit number. In each experiment, when the unmarketable fruit number accounted for more than 50% of the total fruit harvested for three consecutive harvests for all treatments, harvesting was ended. This occurred on 5 (155 DAT) and 16 July (129 DAT) for Expts. 1 and 2, respectively. At the final harvest, all of the remaining fruit were harvested, including green fruit (fruit that was longer than 1 cm but did not reach breaker stage) and fruit at breaker or more advanced ripeness stages. Because green fruit is also an indication of productivity, it is more reasonable to include them in whole-season yield determination. Fruit within each group were further categorized as marketable or unmarketable based on their weight and presence of defects or pest/disease damage. For each experiment, cumulative yield at each week was calculated and plotted. Green fruit were excluded from the cumulative yield curve, but they were considered in the calculation of whole season yields.

Crop vigor assessment after final harvest. After harvest termination, plant stem diameters of all plants in each plot were measured at 3 cm aboveground level using a digital caliper. Plants were destructively sampled on 13 (163 DAT) and 16 July (129 DAT) for Expts. 1 and 2, respectively. The aboveground part of all plants in each plot was harvested and weighed. The harvested aboveground parts from each plot were then cut into small pieces with stem sections no longer than 10 cm and well mixed. Then a subsample of plant pieces of ≈2 kg was taken from each plot. The subsamples were dried in a force-air drying room at 65 °C until constant weight was reached, and the dry weight determined. Dry matter content of the subsamples was calculated as the percent of the dry weight out of the fresh weight and was used to determine the total aboveground dry weight of plans in each plot based on the aboveground fresh weight.

Tomato fruit mineral content at peak harvest. Fruit of 'BHN 1022' and 'Sweet Hearts' from Expt. 1 were sampled at peak harvest on 17 (106 DAT) and 21 May (110 DAT), respectively, for mineral content assessment, and fruit of 'Sweet Hearts' and 'BHN 1022' from Expt. 2 were sampled at peak harvest on 11 (94 DAT) and 18 June (101 DAT), respectively. Marketable fruit from each plot, totaling ≈150 g, were randomly picked and dried at 65 °C for 7 d until constant weight and sent to Waters Agricultural Laboratories (Camilla, GA) to measure the contents of macronutrients, including nitrogen (N), phosphate (P), sulfate (S), potassium (K), calcium (Ca), and magnesium (Mg), and micronutrients, including boron (B), zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu). Marketable fruit percent dry matter was calculated by dividing the dry weight by the fresh weight and multiplying by 100. Fruit mineral contents were reported on both a dry and a fresh weight basis.

Nematode galling assessment. One of the major challenges of growing tomato in Florida is the root-knot nematode (RKN) (*Meloidogyne* spp.) because severe RKN infestation can damage the root system and lead to significant yield loss (Barrett et al., 2012). The RKN species detected in this study was *Meloidogyne javanica*. No other soilborne pathogens were identified in these two experiments. At plant termination, nematode infestation on plant roots was assessed based on galling severity. Roots of each plant from the top 30 cm of the soil and within 30 cm from the main stem were dug up and the soil particles were gently removed. All plants in each plot were assessed for nematode galls using a 0 to 10 rating scale (Zeck, 1971): 0 = no galling, 10 = plant and roots are dead. Two researchers assessed each plant individually and the ratings were averaged for each plot (Barrett et al., 2012).

Statistical analysis. Whole season yield, stem diameter, aboveground dry biomass, and nematode galling rating data were analyzed using the GLIMMIX procedure of SAS (version 9.4; SAS Institute, Cary, NC) following a generalized linear mixed model. Cumulative yields of each harvest week were analyzed separately, as weekly yields varied greatly throughout the harvest period. In Expt. 1, yields of each scion for each harvest week were also analyzed separately due to the rootstock-scion interactions in some harvest weeks. Fisher's least significant difference test at $P \leq 0.05$ was conducted for multiple comparisons of different measurements among treatments.

Results and Discussion

Growing conditions. For Expt. 1, throughout the growing season (from 1 Feb. to 5 July), the average air temperature was 23 °C and RH was 78% (Fig. 1). For Expt. 2, the average air temperature was 24 °C and RH was 80% over the whole season (from 9 Mar. to 16 July). The temperature exceeded 30 °C in February, March, April, May, June, and the first half of July for 91.75 h, 57.25 h, 31.00 h, 50.75 h, 186.25 h, and 122.50 h, respectively. Temperatures above 35 °C occurred in June and in the first half of July for 22.00 h and 41.50 h, respectively.

Whole-season tomato yield components. For Expt. 1, the first harvest of tomato fruit took place 51 DAT. For Expt. 2, the tomato harvest began 63 DAT. Expt. 1 had a harvest window of 104 d, which was 38 d longer than the 66 d harvest window of Expt. 2.

For Expt. 1, no rootstock-scion interactions were detected for any whole-season yield components (Table 1). Fruit yields were similar for self- and nongrafted tomato scions. Rootstocks significantly increased marketable fruit number, marketable yield, and total yield across the different rootstock-scion combinations by 23.3%, 37.9%, and 34.4%, respectively, compared with the average of the self- and nongrafted controls. There was a trending effect ($P = 0.100$) that rootstocks on average increased total fruit number by ≈18.1% compared with the average of self- and nongrafted controls. None of the rootstocks showed any impact on the fruit marketability as calculated by the ratio of marketable to total fruit number or yield (Table 1). All three rootstocks also significantly increased average marketable fruit weight, by 12.0% on average, compared with the self- and nongrafted controls, while average marketable fruit weight of the self- and nongrafted controls did not differ from each other. Despite the similar marketable fruit numbers for both scions, 'BHN 1022' had 22.7% higher average marketable fruit weight than 'Sweet Hearts', leading to 16.0% higher marketable yield (Table 1). Although 'Sweet Hearts' produced 22.5% more in terms of total fruit number than 'BHN 1022', these two scions had similar total yields. 'BHN 1022' also showed higher marketable to total fruit ratios, by 15.9% and 7.2%, based on fruit number and yield, respectively.

Similar to Expt. 1, there was an absence of rootstock-scion interaction effects on fruit yield for Expt. 2 (Table 2). However, in this experiment, rootstocks did not show a significant impact on marketable and total fruit numbers and yields in comparison with the self- and nongrafted controls. Total yields of 'DR0141TX' or 'Estamino'-grafted plants were numerically higher ($P = 0.112$) than the average of self- and nongrafted controls by 37.3% and 34.6%, respectively. Interestingly, in Expt. 2, the rootstocks decreased fruit marketability based on fruit number and yield, by 17.5% and 13.8% on average, respectively, compared with nongrafted controls while no differences in fruit marketability were detected among these three rootstocks (Table 2). However, a significant rootstock effect on increasing average marketable fruit weight was observed in Expt. 2. Grafting with 'DR0141TX' or 'Multifort' led to an 11.5% higher average marketable fruit weight than the average of self- and nongrafted scions, whereas 'Estamino'-grafted plants did not differ from the self- and nongrafted scions. 'DR0141TX'-grafted tomatoes also showed 8.3% higher average marketable fruit weight than 'Estamino'-grafted tomatoes, but the latter did not differ from that of plants grafted with 'Multifort'. Similar to Expt. 1, 'BHN 1022' had higher average marketable fruit weight than 'Sweet Hearts' in Expt. 2 (Table 2). Although 'Sweet Hearts' produced more marketable fruit than 'BHN 1022', both grape tomato cultivars show similar marketable fruit yields. Despite the lack of varietal difference in total fruit number and yield, 'BHN 1022' had lower marketable to total fruit number and yield ratios relative to 'Sweet Hearts', by 11.3% and 13.3%, respectively.

For Expt. 1, the three rootstocks behaved similarly in improving the whole-season marketable and total yields of both grape tomato scions. This was because of increases in both fruit number per plant and average marketable fruit weight, especially for the marketable yield. Our results also showed that the delayed transplanting in Expt. 2 negated the yield benefits of grafting, partially because of failure to extend fruit production into the summer under Florida conditions. Hossain et al. (2019) used 'BARI Tomato-4' (≈50 g/fruit) as scion and reported that rootstock impacts on total fruit number and yield as well as average fruit weight were rootstock cultivar dependent. Albino et al. (2018) and Mauro et al. (2020) also observed the dependence of cherry tomato

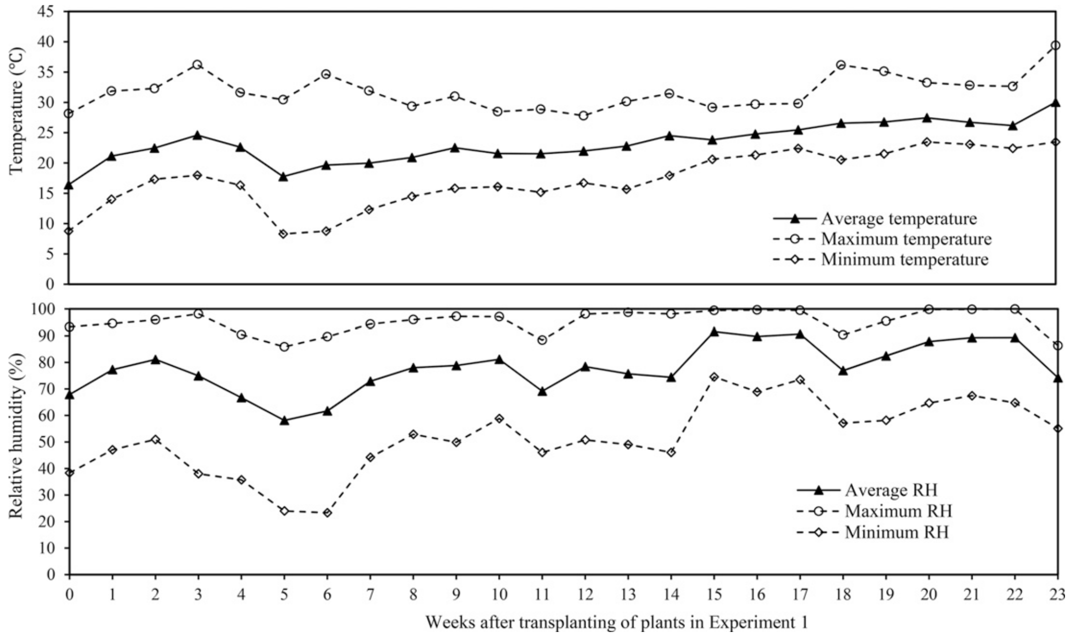

Fig. 1. Weekly average, maximum, and minimum air temperatures and relative humidity (RH) measured at 1 m above the planting bed in the center of the high tunnel from 1 Feb. to 16 July 2018 (data recorded every 15 min). Week 0 represents data recorded during 1 to 3 Feb. 2018; week 23 represents data recorded during 8 to 16 July 2018.

yields on rootstock cultivar or genetic background when compared with the nongrafted scion. Franco et al. (2018) grafted two small fruit tomato cultivars (average weight 50–61 g) and reported that all tested rootstocks decreased average fruit weight, but did not affect fruit number, whereas total fruit yields of grafted plants were either the same or lower than the nongrafted control; this could be because of the short harvest window in their study, as the total yields were only 2.5 to 2.9 kg per plant. The different results could also be attributed to different growing systems, environmental conditions, and specific rootstock-scion combinations, thus more rootstock-scion combinations, especially those with grape tomato, should be tested under different growing conditions. Regardless of different transplanting dates for the two experiments conducted in the present study, similar yield performance between vegetative, generative, and uncharacterized rootstocks suggests that these three rootstock types may not differ in their effects on grape tomato yield in a high tunnel organic production system. More research in different cultivation systems and across multiple seasons is warranted to fully test the rootstock characterization.

When pooled over all rootstock-scion combinations and scion controls, the tomatoes in Expt. 1 showed greater marketable fruit number (by 144.3%), marketable fruit yield (by 92.5%), total fruit number (by 119.8%), and total fruit yield (by 75.8%) compared with Expt. 2. The overall higher tomato yields from Expt. 1 could be largely due to the long-er duration of crop production under the more favorable weather conditions. In June, the duration of exposure to temperatures higher than 30 °C was 267.0% (135.50 h) more than in May and temperatures above 35 °C were not observed in April or May. Abdalla and Verkerk (1968) reported that growing tomatoes under higher temperatures [35/25 °C vs. 22/18 °C (day/night)] led to more flower abscission and declined fruit set as a result of a reduction in pollen tube growth and pollen counts on the stigma. Rivero et al. (2003) also reported that for both grafted and nongrafted tomatoes, 35 °C was high enough to induce heat stress.

In addition to the increased temperature, the average RH was also higher during the late growth stage in both experiments in the present study (Fig. 1). High RH can decrease photosynthetic capacity and have a negative impact on fruit yield (Xu et al., 2006). Plants in Expt. 2 were exposed for a longer time to higher temperatures and RH, especially during the fruiting stage, resulting in an adverse effect on fruit development. Even though much evidence has suggested that selected rootstocks may be used to improve tomato tolerance to certain abiotic stressors [e.g., suboptimal soil

Table 1. Marketable and total yield components of grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 1 (transplanted on 31 Jan. 2018).

Treatment	Marketable fruit no. (no./plant)	Marketable fruit yield (kg/plant)	Total fruit no. (no./plant)	Total fruit yield (kg/plant)	Marketable fruit (% of total no.)	Marketable yield (% of total wt)	Avg marketable fruit wt (g/fruit)
Rootstock (Rs)[z]							
DR0141TX	884.3 a[y]	7.76 a	1240.2	9.53 a	72.3	81.5	8.8 a
Estamino	890.4 a	7.74 a	1134.7	9.15 a	79.4	84.6	8.8 a
Multifort	885.7 a	7.66 a	1133.5	9.16 a	78.5	83.4	8.6 a
Nongrafted	717.9 b	5.73 b	976.7	6.96 b	74.5	82.1	8.0 b
Self-grafted	720.8 b	5.47 b	1003.0	6.85 b	72.5	80.0	7.6 b
Scion (Sc)							
BHN 1022	798.2	7.38 a	986.6 b	8.66	81.0 a	85.2 a	9.2 a
Sweet Hearts	841.4	6.36 b	1208.7 a	8.00	69.9 b	79.5 b	7.5 b
P value							
Rs	0.006	<0.001	0.100	<0.001	0.095	0.317	<0.001
Sc	0.273	0.004	0.002	0.107	<0.001	<0.001	<0.001
Rs × Sc	0.586	0.248	0.891	0.354	0.843	0.897	0.061

[z]DR0141TX: tomato scion grafted onto rootstock ‘DR0141TX’; Estamino: tomato scion grafted onto rootstock ‘Estamino’; Multifort: tomato scion grafted onto rootstock ‘Multifort’; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher’s least significant difference test.

Table 2. Marketable and total yield components of grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 2 (transplanted on 9 Mar. 2018).

Treatment	Marketable fruit no. (no./plant)	Marketable fruit yield (kg/plant)	Total fruit no. (no./plant)	Total fruit yield (kg/plant)	Marketable fruit (% of total no.)	Marketable yield (% of total wt)	Avg marketable fruit wt (g/fruit)
Rootstock (Rs)[z]							
DR0141TX	352.9	4.05	578.2	5.81	60.5 c[y]	70.6 c	11.7 a
Estamino	373.9	3.99	574.9	5.49	64.0 bc	72.5 bc	10.8 bc
Multifort	295.4	3.24	455.4	4.32	64.1 bc	74.8 bc	11.5 ab
Nongrafted	357.4	3.61	467.4	4.26	76.2 a	84.3 a	10.5 c
Self-grafted	298.0	2.96	421.5	3.81	69.4 ab	77.8 ab	10.3 c
Scion (Sc)							
BHN 1022	291.5 b	3.62	461.8	5.15	62.9 b	70.6 b	12.6 a
Sweet Hearts	379.6 a	3.52	537.1	4.33	70.9 a	81.4 a	9.3 b
P value							
Rs	0.596	0.402	0.271	0.112	0.003	0.004	0.012
Sc	0.031	0.798	0.185	0.133	0.003	<0.001	<0.001
Rs × Sc	0.132	0.181	0.146	0.104	0.449	0.486	0.346

[z]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

temperatures (Bristow et al., 2021; Suchoff et al., 2018b) and high salt (Marsic et al., 2018)], growth and development of grafted plants can still be deleteriously affected when exposed to an elevated stress level.

The other factors contributing to the differential effects of grafting between Expts. 1 (early transplanting) and 2 (late transplanting) were pest and disease pressure. In Expt. 1, the tomatoes experienced considerably lower populations of spider mites than the later transplanting. Kennedy et al. (1983) also reported less damage and insect-induced yield losses in early-planted tomatoes compared with late-planted tomatoes. In the present study, fruit with disease and pest problems accounted for 8.5% of total yield based on fruit number and 7.5% based on weight in Expt. 1. In contrast, the marketable fruit yield loss due to disease and pest issues reached 23.3% and 17.3% of total yield based on fruit number and weight, respectively, for Expt. 2, as more fruit showed stink bug damage. The more intensive foliar disease and pest problems encountered in Expt. 2 may have been affected not only by the conducive environmental conditions during the later season, but could also be related to the adjacent early transplanted tomatoes from Expt. 1, which were already harboring some pests and pathogens.

Grieneisen et al. (2018) analyzed data from 735 experimental treatments and found that only 35% of the tomato rootstock-scion combinations assessed yielded significantly higher than self- or nongrafted controls. Our results suggest that such mixed results for grafted tomato yield as affected by rootstocks may largely depend on the production season and site-specific environmental conditions and the associated disease and pest situations that the rootstocks are intended to address, in addition to any rootstock-scion interactions.

Cumulative yield curves. The weekly cumulative yield curves were also examined to help understand fruit yield development dynamics during the harvest season (with green fruit excluded at final harvest). In Expt. 1, rootstock-scion interactions were detected for certain weeks, so cumulative yields of each scion were analyzed separately (Figs. 2 and 3). For 'BHN 1022' treatments, marketable and total fruit cumulative yields increased slowly during the first 6 harvest weeks (HW) and similar yields were observed between grafted and nongrafted plants, except that non- and self-grafted plants showed higher levels than all rootstock treatments at 3 HW (Fig. 2A and B). The weekly cumulative yield increased almost linearly in the middle of the harvest period, with generally a greater weekly increase rate for rootstock-grafted plants relative to non- and self-grafted controls from 7 to 12 HW. 'Multifort' resulted in the highest cumulative yields at 9 and 10 HW, and all rootstocks led to higher cumulative marketable and total yields than non- and self-grafted controls from 11 to 16 HW with no difference among the rootstock treatments. Interestingly, self-grafted 'BHN 1022' produced lower cumulative marketable and total yields than nongrafted plants during 11 to 16 HW. Overall, 'BHN 1022' plants grafted onto the three rootstocks exhibited a similar yielding pattern and outperformed the non- and self-grafted controls during the peak and late harvest periods. A similar trend was observed with the marketable and total cumulative fruit numbers that were generally increased at greater rates for the rootstock treatments compared with the scion controls during 7 to 12 HW (Fig. 2C and D). Although it was more evident that the productivity of rootstock-grafted plants fell behind nongrafted 'BHN 1022' in terms of fruit numbers during the first 3 to 6 weeks of the harvest season, this portion of early yield accounted for <18% of the whole season fruit number. It also needs to be pointed out that the single marketable fruit weight was increased by rootstocks starting 7 HW and this positive impact was more pronounced at 9 to 11 HW with all rootstocks (data not shown), contributing to the higher yields of rootstock-grafted 'BHN 1022' during the peak harvest.

The weekly marketable and total yield patterns of 'Sweet Hearts' treatments differed from 'BHN 1022' in Expt. 1 (Fig. 3). Both marketable and total cumulative yields increased slowly until 6 HW and then climbed almost linearly until 16 HW for rootstock-grafted plants (Fig. 3A and B). In contrast, the cumulative yield increases for self- and nongrafted controls started to slow down from 10 HW. 'DR0141TX' and 'Estamino' resulted in higher cumulative marketable yields than non- and self-grafted controls from 12 to 16 HW and higher cumulative total yields than the nongrafted control at 12 and 13 HW, whereas no difference was found among the rootstock treatments or between non- and self-grafted 'Sweet Hearts' (Fig. 3A and B). The treatment difference in cumulative fruit number was observed at 4 HW with greater marketable and total fruit numbers in 'Multifort'-grafted plants than plants grafted with 'DR0141TX' and 'Estamino' and the nongrafted control (Fig. 3C and D). Moreover, rootstock-grafted plants tended to produce greater marketable fruit numbers at 12 (P = 0.065), 13 (P = 0.074), and 14 (P = 0.087) HW. Compared with the determinate 'BHN 1022' scion, the impact of rootstocks on fruit yield of indeterminate 'Sweet Hearts' appeared later in the harvest season and the green fruit produced at the final harvest exhibited greater influence on the whole season yield.

In Expt. 2, cumulative fruit numbers and yields throughout the harvest were affected by rootstock and scion but not their interactions (Fig. 4). Marketable cumulative yields increased almost linearly from 2 HW until 10 HW for all treatments and then leveled off for the last harvest week (Fig. 4A). Total cumulative yields followed a similar pattern except that they appeared to increase throughout the production season (Fig. 4C). At 2 HW, the nongrafted control had greater cumulative yields and fruit numbers than all three rootstock treatments, whereas the self-grafted control was similar to all other treatments. However, no rootstock effect was observed later in the season (Fig. 4A, C, E, and G). The two tomato scion cultivars did not differ significantly in marketable and total cumulative yields except for during 1 to 4 HW, when 'BHN 1022' was higher than 'Sweet Hearts' (Fig. 4B and D). On the other hand, 'Sweet Hearts' produced greater numbers of

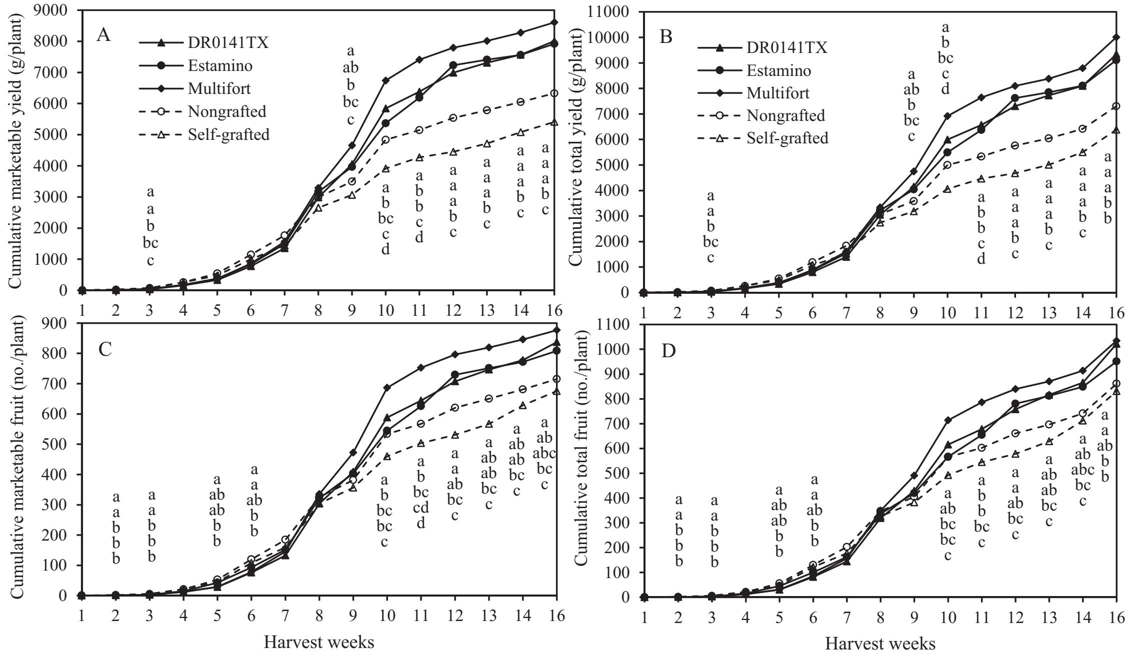

Fig. 2. Cumulative marketable and total fruit yields and numbers of grafted 'BHN 1022' grape tomato in Expt. 1. Green fruit at final harvest were excluded. Harvest started on 23 Mar. and ended on 5 July 2018. For each harvest week, cumulative yields do not statistically differ between treatments when followed by the same letter according to Fisher's least significant difference test at $P \leq 0.05$. (**A**) Cumulative marketable yield of 'BHN 1022'; (**B**) cumulative total yield of 'BHN 1022'; (**C**) cumulative marketable fruit number of 'BHN 1022'; and (**D**) cumulative total fruit number of 'BHN 1022'. No harvest was conducted during week 15, and week 16 represents the last week of harvest. DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

cumulative marketable and total fruit than 'BHN 1022' during 5 to 10 HW (i.e., the middle and later harvest period) (Fig. 4F and H).

In both experiments in the present study, the so-called vegetative and generative rootstocks, 'DR0141TX' and 'Estamino', respectively, showed similar impacts on cumulative marketable and total fruit numbers and yields, which were similar to 'Multifort'. The examination of cumulative yield curves throughout the harvest season highlighted the role of rootstocks in improving grape tomato productivity at peak harvest and maintaining fruit development in the later harvest period. Hence, the yielding potential of grafted plants may be compromised when the harvest season is shortened due to biotic factors and environmental conditions. In a greenhouse study, Djidonou et al. (2017) harvested beefsteak tomato from 63 to 120 DAT and reported that higher total yield from rootstock-grafted plants was

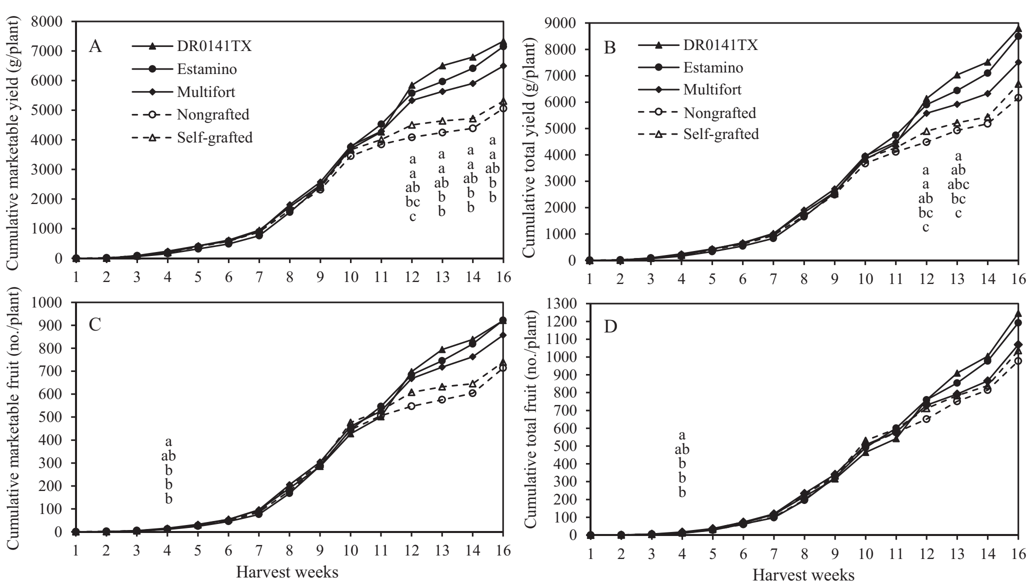

Fig. 3. Cumulative marketable and total fruit yields and numbers of grafted 'Sweet Hearts' grape tomato in Expt. 1. Green fruit at final harvest were excluded. Harvest started on 23 Mar. and ended on 5 July 2018. For each harvest week, cumulative yields do not statistically differ between treatments when followed by the same letter according to Fisher's least significant difference test at $P \leq 0.05$. (**A**) Cumulative marketable yield of 'Sweet Hearts'; (**B**) cumulative total yield of 'Sweet Hearts'; (**C**) cumulative marketable fruit number of 'Sweet Hearts'; (**D**) cumulative total fruit number of 'Sweet Hearts'. No harvest was conducted during week 15, and week 16 represents the last week of harvest. DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

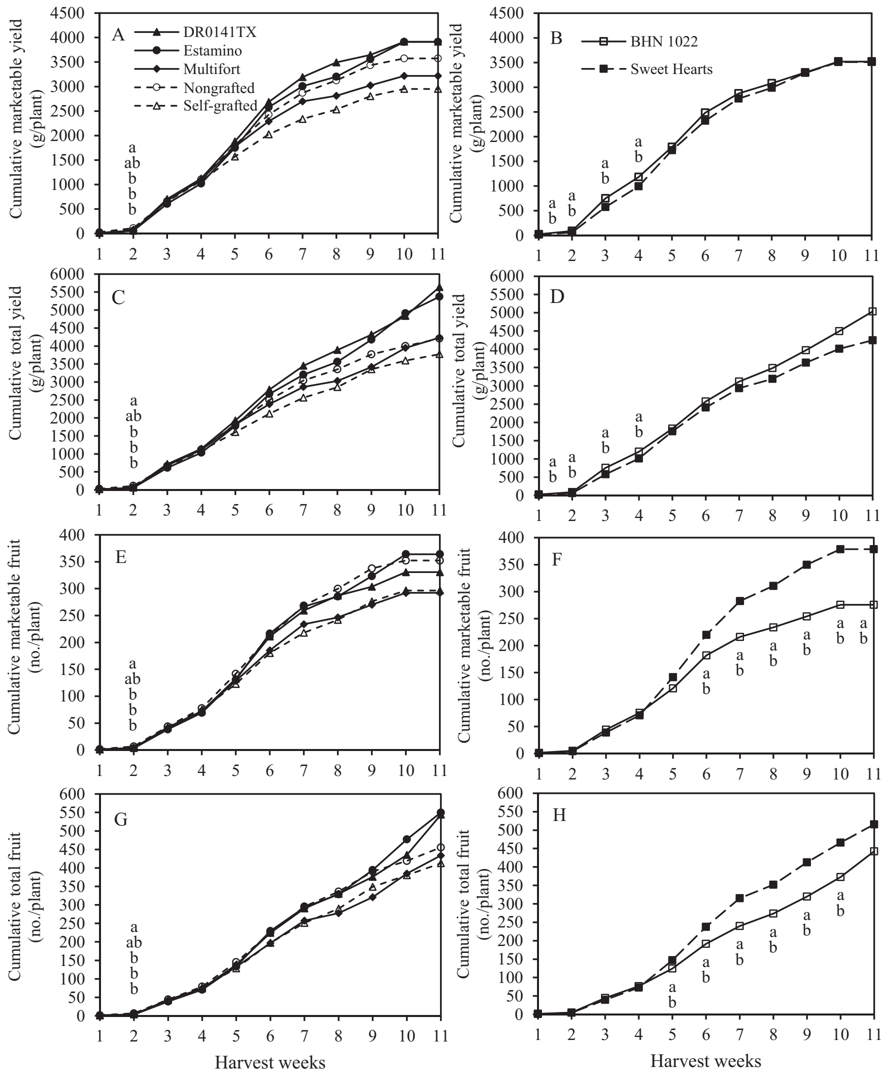

Fig. 4. Cumulative marketable and total fruit yields and numbers of grafted ‘BHN 1022’ and ‘Sweet Hearts’ grape tomatoes in Expt. 2. Green fruit at final harvest were excluded. Harvest started on 11 May and ended on 16 July 2018. For each harvest week, cumulative yields do not statistically differ between treatments when followed by the same letter according to Fisher’s least significant difference test at $P \leq 0.05$. (**A**) Cumulative marketable yield as affected by rootstocks; (**B**) cumulative marketable yield as affected by scions; (**C**) cumulative total yield as affected by rootstocks; (**D**) cumulative total yield as affected by scions; (**E**) cumulative marketable fruit number as affected by rootstocks; (**F**) cumulative marketable fruit number as affected by scions; (**G**) cumulative total fruit number as affected by rootstocks; and (**H**) cumulative total fruit number as affected by scions. DR0141TX: tomato scion grafted onto rootstock ‘DR0141TX’; Estamino: tomato scion grafted onto rootstock ‘Estamino’; Multifort: tomato scion grafted onto rootstock ‘Multifort’; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

ascribed to greater fruit production during the mid and late harvest periods, and enhanced marketable yield was mainly due to higher yield in early and middle harvest periods, which was partially consistent with the findings in Expt. 1 for ‘BHN 1022’. Ramírez-Jiménez et al. (2020) demonstrated similar trends, as grafting a middle-sized tomato (100 g/fruit) cultivar with vigorous rootstocks produced greater yields during the midharvest period, resulting in higher cumulative yields in the last 2 weeks relative to the nongrafted control. In another 2-year greenhouse study of grafted cherry tomatoes by Estévez-Caparrós et al. (2011), grafting impacts on cumulative yield for each week varied with rootstock-scion combinations and years, which were attributed to the rootstock-scion interaction and nonstressful growth conditions.

Crop vigor. In Expts. 1 and 2, consistent trends were observed for stem diameter, as grafting with ‘DR0141TX’ or ‘Multifort’ showed greater stem diameters than the self- and nongrafted controls by 24.3% and 23.5%, respectively (Table 3). ‘Estamino’ was similar to the nongrafted control in Expt. 1 and similar to the self-grafted control in Expt. 2. ‘DR0141TX’-grafted plants had greater stem diameters than ‘Estamino’, by 15.1% and 14.6%, in Expts. 1 and 2, respectively. In Expt. 1, both scions had similar stem diameters, but in Expt. 2, ‘BHN 1022’ stem diameter was 8.3% greater than ‘Sweet Hearts’. In terms of aboveground dry biomass at crop termination, in Expt. 1, all rootstocks increased dry biomass by 74.4% relative to the average of self- and nongrafted controls. In Expt. 2, ‘DR0141TX’ showed a 60.9% increase in aboveground dry biomass, whereas the other rootstock treatments were similar to the controls. In both experiments, ‘Sweet Hearts’ showed greater aboveground biomass than ‘BHN 1022’, which is expected because the former is an indeterminate type (Table 3).

Regardless of rootstock cultivar, and as with stem diameter and aboveground dry biomass, grafted plants in Expt. 1 showed higher growth vigor than the non- and self-grafted tomato scions, which corresponded to significantly higher yield produced in that experiment. Although significant improvement of total yield by rootstocks was lacking in Expt. 2, the higher aboveground biomass at crop termination of the ‘DR0141TX’ treatment was in line with its highest total yield among other treatments in numerical value. In addition, all treatments in Expt. 1 showed thicker stems and greater aboveground dry biomass than the corresponding treatment in Expt. 2, which was consistent with the higher fruit yields also demonstrated in Expt. 1. However, Djidonou et al. (2017) found that grafting impacts on aboveground dry weight at final harvest were rootstock cultivar dependent and were not necessarily associated with yield performance. Mauro et al. (2020) grafted cherry tomatoes of different sizes and demonstrated that plant biomass was mainly determined by scion, which was different from our results. The vegetative rootstock, ‘DR0141TX’, showed greater stem diameter than the generative rootstock, ‘Estamino’, in both experiments, but the aboveground dry biomasses were similar between plants grafted with these two rootstocks. For both experiments, the uncharacterized rootstock, ‘Multifort’, was similar to ‘DR0141TX’ and ‘Estamino’ in stem diameter and aboveground dry biomass.

Mineral nutrient contents in tomato fruit during peak harvest. In Expt. 1, rootstock-scion interactions were not detected for most macronutrients and micronutrients on a dry weight basis except N (Tables 4 and 5). Rootstocks consistently increased fruit P, K, Ca, Zn, and Fe contents by 22.9%, 16.6%, 21.6%, 18.7%, and 30.6%, respectively, compared with the average of self- and nongrafted controls (Table 4). Fruit of ‘DR0141TX’-grafted tomato also had higher P, K, Zn, and Cu contents than ‘Estamino’ by 7.4%, 7.5%, 12.2%, and 26.0%, respectively. Contents of fruit Mg, S, B, and Mn were similar among all treatments. All rootstock-grafted ‘BHN 1022’ had similar N as the nongrafted control, whereas ‘Sweet Hearts’ grafted with ‘DR0141TX’ or ‘Estamino’ had higher fruit N than ‘Multifort’ and the nongrafted control (Table 5). For all rootstock treatments and the nongrafted control, ‘BHN 1022’ fruit had greater N contents than ‘Sweet Hearts’, whereas the self-grafted ‘BHN 1022’ and ‘Sweet Hearts’ did not differ significantly. Similar to Expt. 1, rootstock-scion interactions were not detected for most of the mineral nutrients on

Table 3. Stem diameter, aboveground dry biomass, and nematode galling index rating of grafted grape tomatoes at plant termination as affected by rootstock and scion cultivars in Expt. 1 (transplanted on 31 Jan. 2018) and Expt. 2 (transplanted on 9 Mar. 2018).

Treatment	Stem diam (mm)	Dry biomass (g/plant)	Nematode galling (0–10 rating)[z]
		Expt. 1	
Rootstock (Rs)[y]			
DR0141TX	20.6 a[x]	657.2 a	0.6 c
Estamino	17.9 bc	606.7 a	1.3 bc
Multifort	19.3 ab	573.8 a	2.7 ab
Nongrafted	16.3 cd	344.2 b	3.3 a
Self-grafted	15.8 d	358.1 b	2.2 ab
Scion (Sc)			
BHN 1022	18.1	411.7 b	2.6 a
Sweet Hearts	17.8	604.3 a	1.4 b
P value			
Rs	<0.001	<0.001	0.011
Sc	0.606	<0.001	0.028
Rs × Sc	0.486	0.855	0.285
		Expt. 2	
Rootstock (Rs)			
DR0141TX	15.7 a	506.0 a	1.3 b
Estamino	13.7 bc	432.4 ab	1.1 b
Multifort	14.8 ab	440.4 ab	2.4 ab
Nongrafted	11.8 d	313.6 b	2.3 ab
Self-grafted	12.9 cd	315.3 b	3.3 a
Scion (Sc)			
BHN 1022	14.3 a	342.3 b	2.4
Sweet Hearts	13.2 b	460.8 a	1.7
P value			
Rs	<0.001	0.031	0.021
Sc	0.030	0.011	0.119
Rs × Sc	0.657	0.536	0.452

[z]Root-knot nematode galling index proposed by Zeck (1971).

[y]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[x]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

a dry weight basis in Expt. 2 (Table 6), being significant only for P and Mg (Table 5). Rootstocks increased N, K, Ca, B, Zn, Fe, and Cu by 12.8%, 15.8%, 32.9%, 18.4%, 23.7%, 30.7%, and 45.6%, respectively, compared with the average of self- and nongrafted controls (Table 6). Grafting with 'DR0141TX' or 'Multifort' increased fruit S by 12.0% relative to the self- and nongrafted controls. 'DR0141TX' increased fruit Cu by 18.3% relative to that of 'Estamino'. Grafting with these three rootstocks increased fruit P contents compared with the self- and nongrafted controls for both scions (Table 5). In addition, for 'BHN 1022', 'Multifort' resulted in higher fruit P content than 'DR0141TX' and 'Estamino', but for 'Sweet Hearts', three rootstocks led to similar fruit P contents. 'BHN 1022' and 'Sweet Hearts' had similar fruit P contents when grafted with 'DR0141TX' or 'Estamino', while for 'Multifort'-grafted plants and non- and self-grafted scions, 'BHN 1022' had greater levels of fruit P than 'Sweet Hearts'. All 'BHN 1022' treatments had similar fruit Mg contents, whereas 'Sweet Hearts' grafted onto 'DR0141TX' or 'Estamino' had higher fruit Mg contents compared with the self- and nongrafted controls. Fruit from 'BHN 1022' had greater fruit Mg contents than 'Sweet Hearts', while the degree of increase varied with rootstocks used. Overall, 'BHN 1022' fruit had higher macronutrient and micronutrient contents than 'Sweet Hearts' on a dry weight basis except Fe in Expt. 1 (Tables 4 and 6).

The enhancement of fruit mineral levels by rootstocks found in our study may be largely related to the scion cultivars and growing conditions. Khah et al. (2006) reported that, either under greenhouse or open-field conditions, grafting did not affect fruit Zn, Cu, Mn, and Fe contents compared with the self- and nongrafted plants, whereas Ca content was affected by growing conditions associated with higher rates of water and mineral absorption from the soil by certain rootstocks. When calculated on a dry matter basis, Djidonou et al. (2017) reported that fruit N, K, and Ca contents in grafted 'Florida 47' tomato varied with rootstocks and no rootstock effects on P content were found. However, the accumulation of N, K, Ca, and P in plants did not follow the same patterns as their contents in the fruit. Their study suggested the complex relationship between whole-plant mineral content and fruit mineral content. An increase in whole-plant mineral status may not necessarily guarantee a corresponding increase in the fruit for the same rootstock. More research is needed to understand grafting effects on mineral nutrient status at the whole plant level and its implication at tissue levels to unravel rootstock conferred vigor.

Different from the fruit mineral content results on a dry weight basis, rootstocks showed less pronounced effects on fruit mineral levels on a fresh weight basis (Tables 7 and 8). In both experiments, fruit K, Mg, Ca, and B contents were similar among all treatments, whereas fruit P levels were consistently higher in 'DR0141TX' and 'Multifort' treatments relative to self- and nongrafted controls (Tables 7 and 8). In Expt. 1,

Table 4. Fruit mineral contents on a dry weight (DW) basis in grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 1 (transplanted on 31 Jan. 2018).

	Macronutrient					Micronutrient				
Treatment	P (mg/g DW)	K (mg/g DW)	Mg (mg/g DW)	Ca (mg/g DW)	S (mg/g DW)	B (µg/g DW)	Zn (µg/g DW)	Mn (µg/g DW)	Fe (µg/g DW)	Cu (µg/g DW)
Rootstock (Rs)[z]										
DR0141TX	4.37 a[y]	32.58 a	1.51	1.42 a	1.73	8.71	22.22 a	13.51	47.93 a	6.45 a
Estamino	4.07 b	30.31 b	1.50	1.38 a	1.66	8.42	19.81 b	13.48	45.59 a	5.12 b
Multifort	4.24 ab	32.13 ab	1.55	1.43 a	1.77	8.83	20.45 ab	14.31	45.96 a	5.88 a
Nongrafted	3.43 c	27.43 c	1.43	1.19 b	1.69	8.33	17.45 c	14.18	35.59 b	4.51 bc
Self-grafted	3.45 c	26.90 c	1.44	1.13 b	1.69	8.38	17.63 c	13.25	35.63 b	4.25 c
Scion (Sc)										
BHN 1022	4.08 a	31.42 a	1.64 a	1.49 a	1.91 a	9.18 a	20.13 a	15.32 a	43.33	5.65 a
Sweet Hearts	3.74 b	28.32 b	1.33 b	1.12 b	1.50 b	7.88 b	18.89 b	12.17 b	40.94	4.83 b
P value										
Rs	<0.001	<0.001	0.154	0.005	0.471	0.835	<0.001	0.373	<0.001	<0.001
Sc	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.045	<0.001	0.213	<0.001
Rs × Sc	0.931	0.232	0.110	0.537	0.576	0.477	0.394	0.289	0.114	0.340

[z]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

Table 5. Fruit N, P, and Mg contents in grafted grape tomatoes as affected by rootstock-scion interactions in Expt. 1 (transplanted on 31 Jan. 2018) and Expt. 2 (transplanted on 9 Mar. 2018).

	Expt. 1				Expt. 2					
	N (mg/g DW[y])		N (μg/g FW[y])		P (mg/g DW)		Mg (mg/g DW)		N (μg/g FW)	
Rootstock (Rs)[z]	B[x]	SH	B	SH	B	SH	B	SH	B	SH
DR0141TX	21.35 Aa[w]	17.35 Ba	1526.16 Aa	1285.32 Bab	4.98 Ab	4.70 Aa	1.65 Aa	1.40 Ba	1493.98 Aa	1237.61 Ba
Estamino	19.18 Ab	17.30 Ba	1391.62 Aa	1327.39 Aa	4.90 Ab	4.58 Aa	1.65 Aa	1.40 Ba	1269.76 Ab	1278.09 Aa
Multifort	20.71 Aab	15.43 Bb	1493.16 Aa	1156.06 Bb	5.65 Aa	4.13 Ba	1.80 Aa	1.24 Bab	1261.75 Ab	1371.78 Aa
Nongrafted	20.03 Aab	15.54 Bb	1576.42 Aa	1331.16 Ba	4.33 Ac	3.27 Bb	1.73 Aa	1.18 Bb	1384.47 Aab	1343.79 Aa
Self-grafted	17.03 Ac	17.50 Aa	1380.92 Aa	1434.93 Aa	4.28 Ac	3.35 Bb	1.66 Aa	1.20 Bb	1268.03 Ab	1305.65 Aa
P value										
Rs	0.010		0.243		<0.001		0.419		0.368	
Sc	<0.001		<0.001		<0.001		<0.001		0.448	
Rs × Sc	<0.001		0.012		0.017		0.048		0.036	

[z]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[y]DW = dry weight; FW = fresh weight.

[x]B = 'BHN 1022'; SH = 'Sweet Hearts'.

[w]Means followed by the same uppercase letter within a row and means followed by the same lowercase letter within a column are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

'DR0141TX' and 'Estamino' decreased fruit S contents by 9.6% compared with the self- and nongrafted controls, whereas 'Multifort' showed little influence on the P level of fresh fruit (Table 7). 'DR0141TX' and 'Estamino' also decreased Mn by 14.7% compared with the nongrafted control. However, grafting onto 'DR0141TX' or 'Multifort' increased fruit Cu by 25% compared with the self- and nongrafted controls. In Expt. 2, 'DR0141TX' led to greater levels of fruit Zn and Fe, whereas 'Estamino' and 'Multifort' treatments were similar to the nongrafted controls. Moreover, 'DR0141TX' resulted in the highest fruit Cu content followed by 'Estamino' and 'Multifort', all showing an increase from the self- and nongrafted controls (Table 8). Rootstock-scion interactions were detected for fruit N contents in both experiments (Table 5). In Expt. 1, fruit N contents were similar among all 'BHN 1022' treatments, whereas 'Multifort'-grafted 'Sweet Hearts' had a lower fruit N level than all other treatments except for the 'DR0141TX' treatment. Moreover, for 'DR0141TX' and 'Multifort' treatments and the nongrafted plants, 'BHN 1022' exhibited greater N contents in fruit than 'Sweet Hearts'. In contrast, 'Sweet Heart' treatments were similar in fruit N contents in Expt. 2, whereas 'DR0141TX'-grafted 'BHN 1022' had a greater fruit N content than those grafted with 'Estamino' or 'Multifort' and the self-grafted control. Both scions showed similar fruit N contents on a fresh weight basis except for the 'DR0141TX' treatment in which 'BHN 1022' was found to have a greater level of fruit N than 'Sweet Hearts'. For both experiments, 'BHN 1022' had greater fruit Ca and S levels than 'Sweet Hearts' (Tables 7 and 8). In Expt. 1, 'BHN 1022' and 'Sweet Hearts' had similar levels of fruit P, K, Zn, and Fe, but Mg, B, Mn, and Cu contents were higher in 'BHN 1022' (Table 7). In Expt. 2, 'Sweet Hearts' had higher fruit P, K, Zn, and Fe contents than 'BHN 1022' (Table 8), whereas fruit Mg, B, Mn, and Cu levels were similar between these two scions.

In general, rootstocks showed positive effects on fruit mineral contents on a dry matter basis, but the rootstock influence on fruit nutritive value (as expressed on a fresh weight basis) may be relatively small. The overall disparity among fruit mineral contents when calculated using dry or fresh weight was likely related to the lower dry matter content of rootstock-grafted fruit (data not shown), which was also observed by Turhan et al. (2011) and Djidonou et al. (2016). For most minerals measured in the present study (except for P and Cu in Expt. 1 and P, Zn, Fe, and Cu in Expt. 2), higher water content of fruit from rootstock-grafted plants might dilute the mineral contents leading to similar or even lower mineral contents when calculated on a fresh weight basis. As grape tomatoes are usually consumed as a whole fruit, it would be interesting to know whether rootstocks lead to higher mineral content on a per fruit basis on both fresh and dry weight bases.

Nematode galling assessment. The RKN infestation level was relatively low, as the galling index ratings were between 0.6 and 3.3 for all treatments in both experiments (Table 3). In Expt. 1, grafting with 'DR0141TX' or 'Estamino' significantly reduced the RKN galling index compared with the nongrafted scions, by 71.2% on average. No

Table 6. Fruit mineral contents on a dry weight (DW) basis in grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 2 (transplanted on 9 Mar. 2018).

	Macronutrient				Micronutrient				
Treatment	N (mg/g DW)	K (mg/g DW)	Ca (mg/g DW)	S (mg/g DW)	B (μg/g DW)	Zn (μg/g DW)	Mn (μg/g DW)	Fe (μg/g DW)	Cu (μg/g DW)
Rootstock (Rs)[z]									
DR0141TX	21.45 a[y]	35.79 a	1.90 a	1.69 a	9.25 a	22.50 a	14.00	47.50 a	7.25 a
Estamino	20.36 a	35.05 a	1.95 a	1.64 ab	8.88 a	20.38 b	13.63	44.13 a	6.13 b
Multifort	21.22 a	36.03 a	1.93 a	1.68 a	8.75 a	21.02 ab	13.17	46.00 a	6.63 ab
Nongrafted	18.75 b	30.95 b	1.42 b	1.53 bc	7.38 b	17.81 c	12.88	36.79 b	4.63 c
Self-grafted	18.51 b	30.58 b	1.48 b	1.48 c	7.75 b	16.64 c	12.63	33.41 b	4.53 c
Scion (Sc)									
BHN 1022	23.21 a	36.99 a	2.22 a	1.91 a	9.65 a	20.61 a	15.05 a	45.46 a	6.71 a
Sweet Hearts	16.90 b	30.37 b	1.26 b	1.30 b	7.15 b	18.73 b	11.47 b	37.67 b	4.96 b
P value									
Rs	<0.001	<0.001	0.001	0.008	0.001	<0.001	0.269	<0.001	<0.001
Sc	<0.001	<0.001	<0.001	<0.001	<0.001	0.002	<0.001	<0.001	<0.001
Rs × Sc	0.249	0.140	0.105	0.071	0.297	0.151	0.391	0.196	0.100

[z]DR0141TX: Tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.

[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

Table 7. Fruit mineral contents on a fresh weight (FW) basis in grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 1 (transplanted on 31 Jan. 2018).

	Macronutrient					Micronutrient				
Treatment	P (μg/g FW)	K (μg/g FW)	Mg (μg/g FW)	Ca (μg/g FW)	S (μg/g FW)	B (μg/g FW)	Zn (μg/g FW)	Mn (μg/g FW)	Fe (μg/g FW)	Cu (μg/g FW)
Rootstock (Rs)[z]										
DR0141TX	316.68 a[y]	2363.33	109.62	102.20	125.51 b	0.63	1.61	0.98 b	3.46	0.47 a
Estamino	303.62 ab	2252.05	110.99	102.53	123.46 b	0.63	1.48	1.00 b	3.41	0.38 bc
Multifort	311.24 a	2370.91	114.07	103.99	129.70 ab	0.65	1.50	1.05 ab	3.38	0.43 ab
Nongrafted	280.57 b	2261.69	116.97	96.15	137.67 a	0.68	1.44	1.16 a	2.95	0.37 c
Self-grafted	282.03 b	2198.96	117.31	91.54	137.77 a	0.68	1.44	1.08 ab	2.92	0.35 c
Scion (Sc)										
BHN 1022	305.07	2353.55	123.17 a	111.35 a	143.68 a	0.69 a	1.51	1.15 a	3.23	0.42 a
Sweet Hearts	292.59	2225.23	104.42 b	87.21 b	117.96 b	0.62 b	1.48	0.96 b	3.22	0.38 b
P value										
Rs	0.019	0.513	0.425	0.175	0.040	0.463	0.339	0.021	0.120	<0.001
Sc	0.129	0.096	<0.001	<0.001	<0.001	0.007	0.708	<0.001	0.947	0.009
Rs × Sc	0.925	0.598	0.106	0.497	0.370	0.398	0.598	0.589	0.198	0.490

[z]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.
[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

differences were detected between 'Multifort' and the self- and nongrafted controls. 'Sweet Hearts' had a lower galling index than 'BHN 1022'. In Expt. 2, grafting with 'DR0141TX' or 'Estamino' decreased the galling index by 63.6% compared with the self-grafted control. None of the grafting treatments differed from the nongrafted controls. Both scions showed similar nematode galling indices. Barrett et al. (2012) reported that in a transitional organic field, 'Multifort'-grafted tomato plants showed a root galling rating ≈3.5, which was significantly higher than that of plants grafted with 'Survivor'. However, 'Multifort' produced a comparable yield as 'Survivor', suggesting that 'Multifort' may be able to maintain its root function and overall plant vigor despite nematode infestation, which concurs with our results.

RKN galling index ratings of ≥4 (based on the 0–10 scale) may lead to significant yield losses (Bridge and Page, 1980; Frey et al., 2020). In our study, the generally low RKN pressure as reflected by the galling ratings at ≤3.3 may not have had a marked impact on tomato yield performance. The results of the present study demonstrate that even under low levels of infestation by RKN (and possibly other soilborne pathogens), grafting with selected disease-resistant rootstocks can still improve fruit yield in tomato production, given that there is a positive rootstock-scion synergy.

Conclusions

Season extension achieved by transplanting grafted grape tomatoes early in the Spring season into a high tunnel organic production system significantly improved tomato yield, whereas transplanting later in the same season negated the grafting benefits. Indeterminate grape tomato cultivars can produce more fruit than determinate types, but their whole-season yield difference observed in this study was more related to individual fruit weight. The yield increase associated with early transplanting was mainly due to greater fruit production by grafted plants during the peak and late harvest periods. When calculated on a dry weight basis, contents of P, K, Ca, Zn, and Fe in tomato fruit were increased by all three rootstocks at peak harvest. Given the low level of nematode infestation and an apparent lack of other soilborne diseases present in this study, the rootstock effects observed could be largely attributed to their own intrinsic growth characteristics and their influence on the growth characteristics of the scions. The results of this study of grafted grape tomato production in a high tunnel system do not support the previously proposed designations of "vegetative" and "generative" rootstocks that differ in impacts on tomato yield components. Likewise, data do not support their differences in crop vigor or fruit mineral contents measured on either a dry weight or a fresh weight basis. Instead, findings highlight the importance of considering rootstock × scion × environment interactions in evaluating rootstock effects on tomato scion yield.

Table 8. Fruit mineral contents on a fresh weight (FW) basis in grafted grape tomatoes as affected by rootstock and scion cultivars in Expt. 2 (transplanted on 9 Mar. 2018).

	Macronutrient					Micronutrient				
Treatment	P (μg/g FW)	K (μg/g FW)	Mg (μg/g FW)	Ca (μg/g FW)	S (μg/g FW)	B (μg/g FW)	Zn (μg/g FW)	Mn (μg/g FW)	Fe (μg/g FW)	Cu (μg/g FW)
Rootstock (Rs)[z]										
DR0141TX	311.08 a[y]	2297.62	97.49	120.34	107.44	0.59	1.45 a	0.90	3.05 a	0.46 a
Estamino	299.62 ab	2208.20	95.93	118.00	101.76	0.55	1.30 b	0.85	2.80 ab	0.38 b
Multifort	307.50 a	2267.59	94.56	115.35	103.58	0.54	1.34 ab	0.82	2.89 ab	0.41 b
Nongrafted	277.23 bc	2273.94	105.18	102.04	110.34	0.54	1.31 b	0.93	2.67 b	0.34 c
Self-grafted	266.41 c	2134.30	98.84	100.89	102.05	0.54	1.18 c	0.88	2.35 c	0.31 c
Scion (Sc)										
BHN 1022	276.13 b	2123.69 b	97.65	126.22 a	109.40 a	0.55	1.18 b	0.87	2.61 b	0.38
Sweet Hearts	308.61 a	2348.97 a	99.15	96.43 b	100.67 b	0.55	1.45 a	0.88	2.90 a	0.38
P value										
Rs	0.002	0.341	0.100	0.062	0.059	0.353	0.001	0.434	0.001	<0.001
Sc	<0.001	<0.001	0.544	<0.001	<0.001	0.995	<0.001	0.788	0.005	0.966
Rs × Sc	0.166	0.312	0.119	0.554	0.344	0.870	0.144	0.124	0.384	0.868

[z]DR0141TX: tomato scion grafted onto rootstock 'DR0141TX'; Estamino: tomato scion grafted onto rootstock 'Estamino'; Multifort: tomato scion grafted onto rootstock 'Multifort'; Nongrafted: nongrafted tomato scion control; Self-grafted: self-grafted tomato scion control.
[y]Means within a column followed by the same letter are not significantly different at $P \leq 0.05$ according to Fisher's least significant difference test.

Literature Cited

Abdalla, A.A. and K. Verkerk. 1968. Growth, flowering and fruit-set of the tomato at high temperature. Neth. J. Agric. Sci. 16:71–76.

Albino, V.S., J.R. Peixoto, V. Caetano, and M.S. Vilela. 2018. Rootstock performance for cherry tomato production under organic, greenhouse production system. Hort. Bras. 36:130–135, https://doi.org/10.1590/S0102-053620180122.

Barrett, C.E., X. Zhao, and R. McSorley. 2012. Grafting for root-knot nematode control and yield improvement in organic heirloom tomato production. HortScience 47:614–620, https://doi.org/10.21273/HORTSCI.47.5.614.

Bertin, N. and M. Génard. 2018. Tomato quality as influenced by preharvest factors. Scientia Hort. 233:264–276, https://doi.org/10.1016/j.scienta.2018.01.056.

Borgognone, D., G. Colla, Y. Rouphael, M. Cardarelli, E. Rea, and D. Schwarz. 2013. Effect of nitrogen form and nutrient solution pH on growth and mineral composition of self-grafted and grafted tomatoes. Scientia Hort. 149:61–69, https://doi.org/10.1016/j.scienta.2012.02.012.

Bridge, J. and S.L.J. Page. 1980. Estimation of root-knot nematode infestation levels on roots using a rating chart. Int. J. Pest Manage. 26:296–298, https://doi.org/10.1080/09670878009414416.

Bristow, S.T., L.H. Hernandez-Espinoza, M.S. Bonarota, and F.H. Barrios-Masias. 2021. Tomato rootstocks mediate plant-water relations and leaf nutrient profiles of a common scion under suboptimal soil temperatures. Front. Plant Sci. 11:2281, https://doi.org/10.3389/fpls.2020.618488.

Costa, J.M. and E. Heuvelink. 2018. The global tomato industry, p. 1–26. In: E. Heuvelink (ed.). Tomatoes, 2nd ed. CABI, Boxton, MA.

Djidonou, D., A.H. Simonne, K.E. Koch, J.K. Brecht, and X. Zhao. 2016. Nutritional quality of field-grown tomato fruit as affected by grafting with interspecific hybrid rootstocks. HortScience 51:1618–1624, https://doi.org/10.21273/HORTSCI11275-16.

Djidonou, D., K. Lopiano, X. Zhao, E.H. Simonne, J.E. Erickson, and K.E. Koch. 2015. Estimating nitrogen nutritional crop requirements of grafted tomatoes under field conditions. Scientia Hort. 182:18–26, https://doi.org/10.1016/j.scienta.2014.10.034.

Djidonou, D., X. Zhao, E.H. Simonne, K.E. Koch, and J.E. Erickson. 2013. Yield, water-, and nitrogen-use efficiency in field-grown, grafted tomatoes. HortScience 48:485–492, https://doi.org/10.21273/HORTSCI.48.4.485.

Djidonou, D., X. Zhao, J.K. Brecht, and K.M. Cordasco. 2017. Influence of interspecific hybrid rootstocks on tomato growth, nutrient accumulation, yield, and fruit composition under greenhouse conditions. HortTechnology 27:868–877, https://doi.org/10.21273/HORTTECH03810-17.

Estévez-Caparrós, J.M., M. Díaz-Pérez, and F. Camacho-Ferre. 2011. Influence of several rootstocks on yield of cultivars of pear cherry tomato cultivated under mesh greenhouse. J. Food Agric. Environ. 9:364–368.

Franco, D.A., J.F. Arango, A. Hurtado-Salazar, and N. Ceballos-Aguirre. 2018. Development, production, and quality of 'Chonto' type tomato grafted on cherry tomato introductions. Rev. Ceres 65:150–157, https://doi.org/10.1590/0034-737X201865020006.

Frey, C.J., X. Zhao, J.K. Brecht, D.M. Huff, and Z.E. Black. 2020. High tunnel and grafting effects on organic tomato plant disease severity and root-knot nematode infestation in a subtropical climate with sandy soils. HortScience 55:46–54, https://doi.org/10.21273/HORTSCI14166-19.

Gaion, L.A., L.T. Braz, and R.F. Carvalho. 2018. Grafting in vegetable crops: A great technique for agriculture. Int. J. Veg. Sci. 24:85–102, https://doi.org/10.1080/19315260.2017.1357062.

Goto, R., A. de Miguel, J.I. Marsal, E. Gorbe, and A. Calatayud. 2013. Effect of different rootstocks on growth, chlorophyll a fluorescence and mineral composition of two grafted scions of tomato. J. Plant Nutr. 36:825–835, https://doi.org/10.1080/01904167.2012.757321.

Grieneisen, M.L., B.J. Aegerter, C.S. Stoddard, and M. Zhang. 2018. Yield and fruit quality of grafted tomatoes, and their potential for soil fumigant use reduction. A meta-analysis. Agron. Sustain. Dev. 38:29, https://doi.org/10.1007/s13593-018-0507-5.

Hochmuth, G.J., D. Maynard, C. Vavrina, E. Hanlon, and E. Simonne. 2018. Plant tissue analysis and interpretation for vegetable crops in Florida. 26 June 2022. <https://edis.ifas.ufl.edu/publication/EP081>.

Hossain, M.G., M.A. Ali, R.A. Ripa, S. Ayrin, and S. Mahmood. 2019. Influence of rootstocks on yield and quality of summer tomato cv. 'Bari Tomato-4'. Earth Syst. Environ. 3:289–300, https://doi.org/10.1007/s41748-019-00101-4.

Hu, B., J. Moyseenko, S. Short, S. Walker, and M.D. Kleinhenz. 2015. Eighteen rootstock and five scion tomato varieties: Seedling growth rates before grafting and success in grafting the ninety variety combinations. Midwest Vegetable Trial Report for 2014:165.

Kennedy, G.G., L.R. Romanow, S.F. Jenkins, and D.C. Sanders. 1983. Insects and diseases damaging tomato fruits in the coastal plain of North Carolina. J. Econ. Entomol. 76:168–173, https://doi.org/10.1093/jee/76.1.168.

Khah, E.M., E. Kakava, A. Mavromatis, D. Chachalis, and C. Goulas. 2006. Effect of grafting on growth and yield of tomato (*Lycopersicon esculentum* Mill.) in greenhouse and open-field. J. Appl. Hortic. 8:3–7.

Kumar, P., Y. Rouphael, M. Cardarelli, and G. Colla. 2015. Effect of nickel and grafting combination on yield, fruit quality, antioxidative enzyme activities, lipid peroxidation, and mineral composition of tomato. J. Plant Nutr. Soil Sci. 178:848–860, https://doi.org/10.1002/jpln.201400651.

Leonardi, C. and F. Giuffrida. 2006. Variation of plant growth and macronutrient uptake in grafted tomatoes and eggplants on three different rootstocks. Eur. J. Hort. Sci. 71:97–101.

Lopez-Marin, J., A. Galvez, F.M. del Amor, A. Albacete, J.A. Fernandez, C. Egea-Gilabert, and F. Perez-Alfocea. 2017. Selecting vegetative/generative/dwarfing rootstocks for improving fruit yield and quality in water stressed sweet peppers. Scientia Hort. 214:9–17, https://doi.org/10.1016/j.scienta.2016.11.012.

Marsic, N.K., D. Vodnik, M. Mikulic-Petkovsek, R. Veberic, and H. Sircelj. 2018. Photosynthetic traits of plants and the biochemical profile of tomato fruits are influenced by grafting, salinity stress, and growing season. J. Agr. Food Chem. 66:5439–5450, https://doi.org/10.1021/acs.jafc.8b00169.

Mauro, R.P., M. Agnello, A. Onofri, C. Leonardi, and F. Giuffrida. 2020. Scion and rootstock differently influence growth, yield and quality characteristics of cherry tomato. Plants 9:1725, https://doi.org/10.3390/plants9121725.

Melnyk, C.W. 2017. Plant grafting: Insights into tissue regeneration. Regeneration (Oxf.) 4:3–14, https://doi.org/10.1002/reg2.71.

Ramírez-Jiménez, J.A., C.F. Barrera-Sánchez, and O. de Jesús Córdoba-Gaona. 2020. Yield and yield components of tomato grafted plants in the high Andean region of Colombia. Rev. Colomb. Cienc. Hortic. 14:375–384, https://doi.org/10.17584/rcch.2020v14i3.11671.

Riga, P., L. Benedicto, L. García-Flores, D. Villaño, S. Medina, and Á. Gil-Izquierdo. 2016. Rootstock effect on serotonin and nutritional quality of tomatoes produced under low temperature and light conditions. J. Food Compos. Anal. 46:50–59, https://doi.org/10.1016/j.jfca.2015.11.003.

Rivard, C.L. and F.J. Louws. 2008. Grafting to manage soilborne diseases in heirloom tomato production. HortScience 43:2104–2111, https://doi.org/10.21273/HORTSCI.43.7.2104.

Rivero, R.M., J.M. Ruiz, and L. Romero. 2003. Can grafting in tomato plants strengthen resistance to thermal stress? J. Sci. Food Agr. 83:1315–1319, https://doi.org/10.1002/jsfa.1541.

Sánchez-Rodríguez, E., R. Leyva, C. Constán-Aguilar, L. Romero, and J.M. Ruiz. 2014. How does grafting affect the ionome of cherry tomato plants under water stress? Soil Sci. Plant Nutr. 60:145–155, https://doi.org/10.1080/00380768.2013.870873.

Savvas, D., A. Savva, G. Ntatsi, A. Ropokis, I. Karapanos, A. Krumbein, and C. Olympios. 2011. Effects of three commercial rootstocks on mineral nutrition, fruit yield, and quality of salinized tomato. J. Plant Nutr. Soil Sci. 174:154–162, https://doi.org/10.1002/jpln.201000099.

Suchoff, D.H., J.R. Schultheis, M.D. Kleinhenz, F.J. Louws, and C.C. Gunter. 2018a. Rootstock improves high-tunnel tomato water use efficiency. HortTechnology 28:344–353, https://doi.org/10.21273/HORTTECH04015-18.

Suchoff, D.H., P. Perkins-Veazie, H.W. Sederoff, J.R. Schultheis, M.D. Kleinhenz, F.J. Louws, and C.C. Gunter. 2018b. Grafting the indeterminate tomato cultivar Moneymaker onto Multifort rootstock improves cold tolerance. HortScience 53:1610–1617, https://doi.org/10.21273/HORTSCI13311-18.

Turhan, A., N. Ozmen, M.S. Serbeci, and V. Seniz. 2011. Effects of grafting on different rootstocks on tomato fruit yield and quality. Hort. Sci. (Prague) 38:142–149, https://doi.org/10.17221/51/2011-HORTSCI.

Vicente, M.H., A. Zsögön, A.F.L. de Sá, R.V. Ribeiro, and L.E.P. Peres. 2015. Semi-determinate growth habit adjusts the vegetative-to-reproductive balance and increases productivity and water-use efficiency in tomato (*Solanum lycopersicum*). J. Plant Physiol. 177:11–19, https://doi.org/10.1016/j.jplph.2015.01.003.

Wang, Y., S. Wang, Y. Zhao, D.M. Khan, J. Zheng, and S. Zhu. 2009. Genetic characterization of a new growth habit mutant in tomato (*Solanum lycopersicum*). Plant Mol. Biol. Rpt. 27:431–438, https://doi.org/10.1007/s11105-009-0095-2.

Xu, H.L., D. Iraqi, and A. Gosselin. 2006. Effect of ambient humidity on physiological activities and fruit yield and quality of greenhouse tomato. In XXVII International Horticultural Congress-IHC2006: International Symposium on Advances in Environmental Control. Automation 761:85–92, https://doi.org/10.17660/ActaHortic.2007.761.9.

Zeck, W.M. 1971. Rating scheme for field evaluation of root-knot nematode infestations. Pflanzenschutz nachrichten. 24: 141–144.