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High Tunnel Production of Containerized Hybrid and Heirloom Tomatoes Using Grafted Plants with Two Types of Rootstocks

Jacob Dale Arthur, Tongyin Li *, Geoffrey Thomas Lalk and Guihong Bi

Department of Plant and Soil Sciences, Mississippi State University, Starkville, MS 39762, USA; jda360@msstate.edu (J.D.A.); gtl31@msstate.edu (G.T.L.); gbi@pss.msstate.edu (G.B.)
* Correspondence: tl665@msstate.edu

Abstract: Tomatoes (*Solanum lycopersicum*) are not only one of the most widely grown and consumed vegetables in the U.S., but are also one of the most economically important vegetables for Mississippi growers operating on small- to medium-sized farms. High tunnel production and vegetable grafting serve as effective approaches to provide season extension and improve productivity and resistance to a number of abiotic and biotic factors for tomato plants. Six tomato cultivars, including three hybrids ('Big Beef', 'Early Girl', and 'Sun Sugar') and three heirlooms ('Brandywine', 'Mortgage Lifter', and 'San Marzano'), were evaluated for plant growth, fruit yield, and quality in a containerized high tunnel production system in 2020. Each cultivar was grafted onto two types of interspecific hybrid rootstocks 'Emperador', or 'Maxifort', or grown non-grafted as control. 'Big Beef' and 'Early Girl' produced comparable highest marketable yields of 9.62 to 11.12 kg per plant, compared with 'San Marzano' and 'Sun Sugar' producing the lowest marketable yields of 3.27 to 4.76 kg per plant due to small fruit sizes. Grafting the selected tomato cultivars with the two rootstock types did not alter total marketable yield of any cultivar, but affected overall stem diameter, fruit color, and β-carotene concentrations. The rootstock 'Emperador' decreased soluble solids content and titratable acidity in 'Early Girl' compared to 'Maxifort' grafted or non-grafted plants. The high tunnel enabled early transplanting and resulted in advanced tomato harvest by approximately three to four weeks compared to local field production.

Keywords: *Solanum lycopersicum*; season extension; container production; grafting; *Solanum lycopersicum* × *Solanum habrochaites*; yield; fruit quality

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1. Introduction

Tomatoes are one of the most important vegetable crops produced and consumed in the United States (U.S.) with an industry value of USD 1.67 billion in 2017 [1,2]. Per capita consumption of fresh and processed tomatoes were 20.3 pounds (9.21 kg) and 73.3 pounds (33.2 kg) in 2017, respectively [2]. Tomatoes are grown on approximately 400 acres (162 ha) in Mississippi, serving as one of the most economically important vegetables in the state [3]. Tomatoes produced in Mississippi are mostly marketed for fresh consumption through local farmers markets, community supported agriculture (CSA), local restaurants, and on-farm or roadside stands [4]. Fresh tomatoes are of the favorite items among local consumers in Southern U.S. Consumers are willing to pay a premium price for overall flavor and physical appearance.

There has been an increasing interest among U.S. growers in using season extension tools, such as high tunnels, to increase profitability [5]. High tunnels are constructed with metal frames covered with polyethylene films, depend on passive solar radiation and ventilation to increase temperature, and extend growing season into early spring and late fall [6,7]. They can decrease frost risks, enable early transplanting and early harvest, and were reported to increase yield and quality for a number of specialty crops, including vegetables, cut flowers, and small fruits [8–10]. When used in tomato production, high tunnels were shown to improve fruit yield with a greater number of marketable fruit per plant and move up fruit harvest for three weeks compared to open field production [11,12]. Exclusion of rain under the high tunnel reduces certain foliar diseases, including early blight (*Alternaria solani*), bacterial speck (*Pseudomonas syringae* pv. *tomato*), and pest problems, including whiteflies (*Bemisia tabaci*), thrips (*Frankliniella* spp.), and aphids (*Aphis gossypii*) for tomatoes [13–16]. Relative off-season production can result in significant market premium and improve profitability for local growers. Unit price for a high tunnel ranges from USD 24.2 to 53.8 per square meter, making high tunnel economical season extension tools for growers operating on small to medium sized farms compared to a greenhouse [17].

Grafting has been successfully used in a number of fruiting vegetables in the Solanaceae and Cucurbitaceae families including tomatoes, peppers *(Capsicum annuum* L.), eggplants (*Solanum melongena* L.), and cucumbers (*Cucumis sativus* L.) to improve plant vigor, resistance to soilborne diseases, adaptability to abiotic stresses, and improve productivity [15,18–25]. Tomato cultivar 'Monroe' (*L. esculentum mill.*) produced significantly higher fruit yield per plant when grafted onto 'Beaufort' rootstock compared with non-grafted plants. This increased fruit yield was attributed to vigorous root system of the rootstock [26]. Bacterial wilt (*Ralstonia solanacearum*) was effectively controlled for tomato production in open field when heirloom variety 'German Johnson' were grafted onto CRA 66 or Hawaii 7996 rootstock [27]. The adoption of grafted tomato plants in the U.S. has been slower than Asian countries partially due to the labor-intensive nature of plant grafting and high plant cost compared to non-grafted seedlings [23,28,29]. The benefit of using grafted plants against high plant costs in a certain production system and climatic conditions remains unclear and merits investigation.

Tomato rootstocks of various genotypes are commercially available, with the benefit of grafting largely depending on the rootstock and scion type [19,30–33]. The hybrid rootstocks 'Survivor' and 'Multifort' showed similar effects in significantly reducing root galling caused by root-knot nematodes (*Meloidogyne* spp.) in an organic field compared to non-grafted or self-grafted plants, but different effects ('Survivor' superior to 'Multifort') in a transitional filed when using two heirloom cultivars 'Brandywine' and 'Flamme' as scions [20]. Interspecific hybrid rootstocks (*Solanum lycopersicum* × *Solanum habrochaites*) 'Beaufort', 'Maxifort', 'Multifort', and 'RST-04-105′ increased marketable and total yields of 'Florida 47′ by 66% and 53% compared to non-grafted and self-grafted plants under greenhouse conditions [32]. Selecting an appropriate rootstock for tomato cultivars adapted to a certain production system and local climate is critical in using grafted tomato plants considering that the interaction between the rootstock and scion can vary greatly [1,29]. Cultivar specific response to selected rootstocks requires investigation.

The objectives of this study were to: (1) investigate plant growth, fruit production timing, yield, and quality of six tomato cultivars grown in containers under a high tunnel production system; and (2) compare performance among three plant types, including grafted plants with two types of rootstocks and non-grafted seedlings.

2. Materials and Methods

2.1. Plant Culture and Management

The experiment was conducted in a high tunnel at the R.R. Foil Plant Science Research Center of Mississippi State University (lat. 33.45° N, long. 88.79° W; USDA hardiness zone 8a) during the 2020 growing season. The high tunnel was placed in full sun, oriented north to south, and measures 29.0 m long by 9.1 m wide. The high tunnel has metal frames covered with 0.15 mm clear polyethylene film and has side curtains and two doors on end walls opening to 1.5 and 3 m high, respectively (Tubular Structure, Lucedale, MS, USA). Side curtains and end doors of the high tunnel were closed when air temperature dropped below 10 °C, and otherwise remained open within the experiment duration.

Six indeterminate tomato cultivars including three hybrids ('Big Beef', 'Early Girl', and 'Sun Sugar') and three heirloom cultivars ('Brandywine', 'Mortgage Lifter', and 'San Marzano') were tested in this study. Each cultivar was grafted onto two types of interspecific hybrid rootstocks (*Solanum lycopersicum* × *Solanum habrochaites*) 'Emperador' or 'Maxifort'. Non-grafted seedlings of each cultivar were grown as control to grafted plants. Grafted plants were purchased from Log House Plants (Cottage Grove, OR, USA). Seeds of each cultivar were purchased from Totally Tomatoes (Randolph, WI, USA). Non-grafted transplants were prepared in a greenhouse on campus of Mississippi State University in January 2020 using a soilless substrate (PRO-MIX BX General Purpose, Premier Tech Horticulture, QC, Canada) in 32-cell plug trays (T.O. Plastics, Clearwater, MN, USA). Grafted tomato plants were received when six weeks old and were transplanted into the same 32-cell trays and soilless substrate as used for the non-grafted plants. All tomato transplants, grafted and non-grafted, were fertigated with a general purpose fertilizer (Peters® Professional 20-20-20 General Purpose; ICL Specialty Fertilizers, Summerville, SC, USA) at a rate of 100 ppm N three times per week during establishment. The greenhouse had air temperature set at 25 °C and natural light. Transplants of the six tested cultivars (10 weeks old) of uniform sizes, grafted or non-grafted, were transplanted into the high tunnel on 25 March, 2020, and were hardened off one week prior to planting.

Tomato plants were grown in 6-gallon (23 L) containers (height: 29.21 cm; top diameter: 35.6 cm; C2800, Nursery Supplies, Chambersburg, PA, USA) with a peat-based soilless substrate (PRO-MIX BX General Purpose, Premier Tech Horticulture, QC, Canada) spaced 0.6 m apart center to center. Micronutrients (Micromax; ICL Specialty Fertilizers) at a rate of 0.89 $kg \cdot m^{-3}$ and granular lime (Soil Doctor Pelletized Lawn Lime; Oldcastle, Atlanta, GA, USA) at a rate of 2.97 $kg \cdot m^{-3}$ were incorporated into the substrate pre-planting. Tomato plants were drip irrigated with two emitters per container (1.89 L per hour, Netafim, Fresno, CA, USA) as needed. A two-part fertigation system consisting of part A 5N-5.2P-21.6K (5-12-26, Jack's Nutrient, JR Peters Inc., Allentown, PA, USA) and part B 15N-0-0 (15-0-0,) was used to provide nutrients for tomato plants. The two soluble fertilizers were injected with two separate injectors (D14MZ2; Dosatron Intl. Inc., Clearwater, FL, USA) at rates of 50 ppm N of part A and 100 ppm N of part B, respectively.

A trellis system was constructed in the high tunnel to function similarly to an overhead trellising with rebar posts. Six rebars (3 m. long, 2.5 cm in diameter) were placed in each linear row (block, or replication) of 27 m with approximately 5.4 m spacing and placed 0.5 m in ground (Figure S1). High tensile vineyard wire (12.5 gauge) was attached on top of the rebar posts in each row to install individual strings. Rebar posts at the two ends of each row were anchored with ground wire, steel shed anchors (1 m), and in-line tighteners to help support plant weight and remain a vertical position. Tomato plants were trained to have one main stem and clipped onto a cotton string attached to the top wire with new clips being added once per week as plants grew. During the growing season, tomato plants were pruned weekly to remove suckers, dead, or diseased leaves.

For pest management, fungicides including mancozeb, penthiopyrad, famoxadone, and cymoxanil were used to control leaf diseases. Insecticides including zeta-cypermethrin, pyriproxyfen, and acetamiprid were used to control tomato horn worms *(Manduca quinquemaculata*), tomato fruit worms (*Helicoverpa zea*), and whiteflies (*Trialeurodes vaporariorum*). All pesticides were recommended by plant pathologist and entomologist at Mississippi State University and applied following product labels.

2.2. Microenvironment in the High Tunnel

A temperature and relative humidity (S-THB-M00x; Onset Computer Corporation, Bourne, MA, USA) sensor and a quantum sensor (S-LIA-M003; Onset Computer Corporation) were installed and connected to a Micro Station (H21-USB; Onset Computer Corporation) at the center of the high tunnel. Air temperature, relative humidity, photosynthetic active radiation *(PAR*) were recorded at one-hour intervals. Daily light integral (DLI) was calculated by multiplying daily average *PAR* with 0.0864 as described by Torres and Lopez [34]. Air temperatures, relative humidity, and DLI in the high tunnel were presented in Figure S2.

2.3. Plant Vegetative Growth

Before fruit harvest, each tomato plant was measured for plant height and relative leaf chlorophyll content measured as soil plant analysis development (SPAD) readings at 28 and 54 days after planting (DAP). Plant height was measured from the substrate surface to the growing tip on each plant. Leaf SPAD for each plant was measured from three fully expanded leaves on the terminal leaflet using a chlorophyll meter (SPAD 502 Plus; Konica Minolta, Inc., Osaka, Japan). Three readings collected from three individual leaves were averaged to represent leaf SPAD for a given plant. Stem diameter was measured once at 54 DAP, where stem diameter at 15 cm above substrate surface was measured on each plant using a digital caliper.

2.4. Tomato Harvest and Yield Measurement

Tomato fruits were harvested at the breaker stage or later, as described by Djidonou et al. [32], every four to five days throughout the season as appropriate. Tomato fruit at each harvest was sorted for blossom end rot, cracking, catfacing, disease or insect damaged fruits and recorded as unmarketable yield. Total, marketable, unmarketable yields, as well as the number of fruits in each category were recorded for every plant at each harvest. Each fruit was weighed for individual fruit size for five cultivars except for the cherry tomato 'Sun Sugar', where its fruit size was calculated by dividing total marketable yield by the number of fruits given the large number of fruit at each harvest. Fruit was harvested 16 times from 25 May (61 DAP) to 21 August 2020 (143 DAP). The entire growing season was broken approximately monthly into early (25 May–26 June), middle (2 July–27 July), and late (1 August–21 August) season. Fruit yield (total, marketable, or unmarketable) in each period was estimated by summing yields from harvests during that time. Season total was also calculated by summing yields in a given category from all 16 harvests.

2.5. Fruit Firmness, Soluble Solids Content (SSC), Titratable Acidity (TA), and Juice pH

Fruit firmness was assessed as the maximum penetrating force (N) during tissue breakage using a digital fruit firmness tester and a 2-mm diameter tip (FR-5120; Lutron Electronic Enterprise CO., LTD, Taipei, Taiwan). Two firmness readings were collected from two individual marketable fruits for each plant. Marketable fruit of appropriate weight from each plant was manually juiced and filtered through cheese cloth for measurements of SSC and TA. Fruit soluble solids content was measured using a digital refractometer (PR-32α; Atago U.S.A., Inc., Bellevue, WA, USA). Titratable acidity of tomato juice was measured using an automated titrator (EasyPlus; Mettler Toledo, Columbus, OH, USA). For each TA measurement, 5 mL of juice was diluted with 80 mL of deionized water. The mixture was then titrated by 0.1 M sodium hydroxide to an end point of pH 8.2. Titratable acidity of tomato juice was expressed as percentage of citric acid equivalent. Initial juice pH was also measured by the titrator during TA measurement. Two sets of firmness, SSC, and TA data were collected using fruits from early-to-mid season and from late season. Fresh tomato fruit of 100 g from each plant was then frozen for lycopene and β-carotene measurement.

2.6. Fruit Color, Lycopene, and β-Carotene Concentrations

Tomato color at the red stage were measured using a chroma meter (CR-400, Konica Minolta Sensing Americas Inc., Ramsey, NJ, USA) with two readings per fruit measured near the blossom end. One fruit per plant was measured for absolute colors using the L*, a*, b* coordinates, where L* indicates lightness, a* is the red/green coordinate, and b* is the yellow/blue coordinate.

Frozen fruit sample from each fruit was thawed at 4 °C and homogenized using a laboratory blender (Conair™ Waring™, single speed, Waring Laboratory Science, Stamford, CT, USA) for lycopene and β-carotene extractions. Homogenized tomato sample of 1 g was weighed into a 50 mL centrifuge tube and added 16 mL acetone/hexane (2:3, *v*:*v*) solvent for extraction as described by Djidonou et al. [32] and Nagata and Yamashita [35].

The mixture was placed at −20 °C for 60 min, followed by vortex shaking for 30 s at high speed. Two phases were separated after shaking. An aliquot of 200 µL from the upper phase was measured for absorbance (A) at four wavelengths: 663, 645, 505, and 453 nm by a microplate spectrophotometer (Epoch II, BioTek Instruments, Winooski, VT, USA) with three subsamples. The lycopene and β-carotene concentration (mg per g FW) in each sample was calculated using the following equations: lycopene = $-0.0458 \times A663 + 0.204 \times A645 + 0.372 \times A505 - 0.0806 \times A453$; β-carotene = $0.216 \times A663 - 1.22 \times A645 - 0.304 \times A505 + 0.452 \times A453$.

2.7. Experimental Design and Data Analyses

This experiment had a factorial arrangement of treatment conducted in a randomized complete block design with five replications. Within a replication, each treatment combination had two single plant subsamples. The two experimental factors were tomato cultivar (6) and plant type (3, including grafted plant with 'Maxifort' rootstock, grafted plant with 'Emperador' rootstock, and non-grafted seedling), resulting in 18 treatment combinations. Data from this study were analyzed by two-way analysis of variance (ANOVA) using the PROC GLIMMIX procedure in SAS (version 9.4; SAS Institute, Cary, NC, USA). Means were separated by Tukey's Honest Significance Difference Test (HSD) at $\alpha < 0.05$.

3. Results

3.1. Plant Vegetative Growth

Plant height at (28 and 54 DAP) was affected by the interaction between cultivar and plant type (Table 1). Plant height ranged from 43.5 cm in non-grafted 'San Marzano' to 60.3 cm in non-grafted 'Big Beef', with 'Big Beef' generally producing the greatest heights and 'San Marzano' producing the lowest. The three plant types generally had similar height within one cultivar except that 'Maxifort' grafted plants produced lower height of 47.1 cm than non-grafted 'Brandywine' of 55.6 cm. At 54 DAP, five cultivars including 'Big Beef', 'Brandywine', 'Early Girl', 'Mortgage Lifter', and 'Sun Sugar' generally had similar heights regardless of plants being grafted or not. 'San Marzano' produced the lowest plant height of 79.3 cm to 97.8 cm among cultivars. The three plant types produced similar height within each cultivar at 54 DAP.

Table 1. Plant vegetative growth of six tomato cultivars when grafted onto two types of rootstocks or grown non-grafted in a high tunnel during the 2020 growing season.

		28 DAP [2]		54 DAP		
Cultivar	**Plant Type [1]**	**Plant Height (cm)**	**SPAD**	**Plant Height (cm)**	**SPAD [3]**	**Stem Diameter (mm)**
Big Beef	Emperador	58.6 ab	48.2 a–d	118.6 a	56.0 b	15.6 bc
	Maxifort	59.0 ab	48.5 a–d	112.1 abc		
	Non-grafted	60.3 a	49.0 a–d	126.2 a		
Brandywine	Emperador	52.9 b–f	46.9 bcd	112.1 abc	52.6 bc	14.6 c
	Maxifort	47.1 fg	45.3 d	105.5 abc		
	Non-grafted	55.6 a–d	51.3 abc	107.8 abc		
Early Girl	Emperador	51.2 c–f	51.9 ab	98.3 bcd	51.9 c	17.8 ab
	Maxifort	53.4 a–f	48.0 a–d	112.1 abc		
	Non-grafted	53.1 b–f	48.5 a–d	117.5 ab		
Mortgage Lifter	Emperador	52.5 b–f	45.6 d	123.4 a	51.3 c	17.3 ab
	Maxifort	53.7 a–f	48.8 a–d	120.9 a		
	Non-grafted	54.8 a–e	46.0 cd	113.7 abc		

Table 1. *Cont.*

		28 DAP [2]			54 DAP	
Cultivar	**Plant Type** [1]	**Plant Height**	**SPAD**	**Plant Height**	**SPAD** [3]	**Stem Diameter**
San Marzano	Emperador	49.5 d–g	48.3 a–d	96.0 cd	49.0 c	19.7 a
	Maxifort	48.4 efg	47.8 bcd	97.8 cd		
	Non-grafted	43.5 g	45.1 d	79.3 d		
Sun Sugar	Emperador	57.6 abc	51.7 ab	122.7 a	60.2 a	16.0 bc
	Maxifort	57.5 abc	50.3 a–d	124.2 a		
	non-grafted	56.1 a–d	53.4 a	126.6 a		
p-value	Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Plant type	0.67	0.45	0.99	0.27	<0.0001
	Cultivar*Type	0.0008	0.0002	0.0006	0.07	0.24

[1] Each cultivar was grafted onto two types of rootstocks 'Emperador' and 'Maxifort', or grown non-grafted as control. [2] Different lower case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$. [3] To present the main effect of cultivar, means for SPAD and stem diameter were obtained by averaging data over all three plant types.

Leaf SPAD readings were affected by the interaction between cultivar and plant type at 28 DAP, ranging from 45.1 in non-grafted 'San Marzano' to 53.4 in non-grafted 'Sun Sugar' (Table 1). Grafted and non-grafted plants generally had similar leaf SPAD within a given cultivar except that 'Maxifort' resulted in lower leaf SPAD than non-grafted plants in 'Brandywine'. Leaf SPAD readings at 54 DAP varied among tomato cultivars, with no significant influence from plant type or interaction. 'Sun Sugar' produced the highest SPAD reading of 60.2 among cultivars, with 'Big Beef' producing the second highest SPAD of 56.0. 'Brandywine', 'Early Girl', 'Mortgage Lifter', and 'San Marzano' had similar leaf SPAD ranging from 49.0 to 52.6.

Stem diameter at 54 DAP varied among cultivars and plant types separately without interaction (Table 1). Four cultivars 'Big Beef', 'Early Girl', 'Mortgage Lifter', and 'Sun Sugar' had similar stem diameters from 15.6 to 17.8 mm. 'San Marzano' produced the highest stem diameter of 19.7 mm, and 'Brandywine' produced the lowest stem diameter of 14.6 mm. 'Emperador' rootstock resulted in the largest stem diameter of 19.3 mm across tomato cultivars, and 'Maxifort' rootstock resulted the intermediate stem diameter of 17.3 mm, both higher than those from non-grafted plants of 13.9 mm (Table 2).

Table 2. Plant growth and fruit quality of tomato cultivars affected plant type in a high tunnel during the 2020 growing season.

		Color		
Plant Type [1]	**Stem Diameter** [2,3] **(mm)**	**a***	**b***	**β-Carotene ($\mu g \cdot g^{-1}$ FW)**
Emperador	19.3 a	25.2 b	27.5 b	16 ab
Maxifort	17.3 b	26.4 a	28.6 a	12.9 b
Non-grafted	13.9 c	26.2 ab	28.4 ab	22.7 a
p-value	<0.0001	0.02	0.02	0.003

[1] Tomato cultivars were grafted onto two types of rootstocks 'Emperador' and 'Maxifort', or grown non-grafted as control. [2] Means of each plant type were obtained by averaging data over all six tomato cultivars. [3] Different lower case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$.

3.2. Fruit Yield Component

Marketable yields were affected by the interaction between cultivar and plant type in June and August but varied among cultivars in July (Table 3). 'Big Beef' of any plant type, 'Maxifort' grafted and non-grafted 'Early Girl' produced the highest marketable yields in June ranging from 3.61 to 5.01 kg per plant. 'Mortgage lifter', 'San Marzano', and 'Sun Sugar' of any plant type produced the lowest yields of 0.99 to 2.30 kg per plant. In

July, the two hybrid cultivars 'Early Girl' and 'Big Beef' produced the comparable highest marketable yields of 4.96 and 4.01 kg per plant, respectively. The three heirloom cultivars 'Brandywine', 'Mortgage Lifter', and 'San Marzano' produced similar marketable yields ranging from 2.40 to 3.38 kg per plant, with the cherry tomato 'Sun Sugar' producing the lowest marketable yield of 1.77 kg per plant. For late season yield in August, 'Big Beef' and 'Early Girl' of any plant type, and 'Maxifort' grafted 'Brandywine' produced comparably highest marketable yields of 1.42 to 2.21 kg per plant, with all other treatment combinations producing similar yields. Three plant types generally produced similar marketable yields except that 'Emperador' decreased June yield in 'Brandywine' compared with 'Maxifort', and that non-grafted plants increased August yield compared with grafted plant of any type in 'Mortgage Lifter'.

Total marketable yield, fruit number, and total unmarketable yield were all affected by the interaction between cultivar and plant type (Table 3). 'Big Beef' and 'Early Girl' of any plant type, 'Maxifort' grafted 'Brandywine', and non-grafted 'Mortgage Lifter' produced comparably highest total marketable yields ranging from 7.92 to 11.12 kg per plant. All other treatment combinations including 'San Marzano' and 'Sun Sugar' of any plant type, 'Emperador' and non-grafted 'Brandywine', and 'Emperador' and 'Maxifort' grafted 'Mortgage Lifter' produced similarly total marketable yields of 3.27 to 5.78 kg per plant. Plant type did not cause difference in total marketable yield within any given cultivar.

The cherry tomato cultivar 'Sun Sugar' produced the highest marketable fruit number of 258 to 321 per plant, higher than any other cultivar regardless of plant type (Table 3). 'Big Beef', 'Brandywine', and 'Mortgage Lifter' produced the lowed marketable fruit number of 15.7 to 42.6 per plant. 'Early Girl' and 'San Marzano' produced intermediate fruit number of 46.3 to 81.4 fruits per plant. Three plant types generally produced similar fruit number per plant, except that the two grafted 'Sun Sugar' plants produced higher fruit number than non-grafted plants.

Total unmarketable yields were the highest in 'Emperador' grafted 'Brandywine' (2.53 kg per plant), 'Mortgage Lifter' grafted to 'Emperador' (1.78 kg per plant), or 'Maxifort' (2.53 kg per plant) (Table 3). All other treatment combinations produced generally similar total unmarketable yields of 0.21 to 1.29 kg per plant.

Season total yield varied among cultivars and was not affected by plant type, with the two hybrid cultivars 'Big Beef' and 'Early Girl' producing the highest total yields of 11.34 and 10.47 kg per plant. The two heirloom cultivars 'Brandywine' and 'Mortgage Lifter' producing intermediate yields of 8.08 and 8.22 kg per plant. 'San Marzano' and 'Sun Sugar' produced the lowest total yields of 4.48 and 4.33 kg per plant.

3.3. Fruit Size

The average fruit size varied among tomato cultivars and was not affected by plant type (Table 3). 'The ranking of fruit size was 'Mortgage Lifter' (386.8 g per fruit) > 'Brandywine' (340.3 g per fruit) > 'Big Beef' (261.0 g per fruit) > 'Early Girl' (146.1 g per fruit) > 'San Marzano' (70.7 g per fruit) > 'Sun Sugar' (14.3 g per fruit).

Table 3. Yield components and fruit size of six tomato cultivars when grafted onto two types of rootstocks or grown non-grafted in a high tunnel in 2020.

Cultivar	Plant type [1]	Marketable Yield [2,3] (kg per Plant)			Total Marketable Yield (kg per Plant)	Total Unmarketable Yield (kg per Plant)	Total Yield (kg per Plant)	Marketable Fruit Number	Fruit Size (g per Fruit)
		June	July	August					
	Emperador	5.00 a		1.44 a–e	10.45 a	0.73 b–d		38.9 d–f	
Big Beef	Maxifort	5.01 a	4.01 ab	2.21 a	11.12 a	0.84 b–d	11.34 a	40.8 d–f	261.0 c
	Non-grafted	4.62 ab		1.71 a–c	10.60 a	0.71 b–d		42.6 d–f	
	Emperador	1.76 fg		0.70 e–f	5.65 b–d	2.53 a		16.7 f	
Brandywine	Maxifort	3.39 b–e	3.13 bc	1.42 a–e	8.40 ab	0.92 b–d	8.08 b	26.1 f	340.3 b
	Non-grafted	2.60 d–f		0.61 e–f	5.67 b–d	1.30 bc		18.2 f	
	Emperador	2.68 c–f		1.48 a–d	9.62 a	0.25 cd		81.4 c	
Early Girl	Maxifort	4.12 abc	4.96 a	1.95 a	10.70 a	0.38 cd	10.47 a	65.4 cd	146.1 d
	Non-grafted	3.61 a–d		1.74 ab	10.22 a	0.40 cd		67 cd	
	Emperador	2.10 efg		0.34 f	5.78 b–d	1.78 ab		20.9 f	
Mortgage Lifter	Maxifort	2.30 d–g	3.38 bc	0.75 c–f	5.73 b–d	2.53 a	8.22 b	15.7 f	386.8 a
	Non-grafted	2.01 efg		2.27 a	7.92 a–c	1.29 bc		23.4 f	
	Emperador	1.12 g		0.70 d–f	4.33 d	0.33 cd		55.1 c–e	
San Marzano	Maxifort	1.03 g	2.40 cd	0.86 b–f	4.58 d	0.27 cd	4.48 c	60.8 cd	70.7 e
	Non-grafted	0.99 g		0.36 f	3.27 d	0.65 cd		46.3 def	
	Emperador	1.91 fg		0.49 ef	4.14 d	0.22 d		293 a	
Sun Sugar	Maxifort	2.20 d–g	1.77 d	0.47 f	4.76 cd	0.21 d	4.33 c	321 a	14.3 f
	Non-grafted	1.67 fg		0.42 f	3.60 d	0.22 d		258 b	
p-value	Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Plant type	0.0021	0.60	0.0008	0.05	0.20	0.07	0.0031	0.07
	Cultivar*Type	0.045	0.44	<0.0001	0.046	<0.0001	0.51	<0.0001	0.2

[1] Each cultivar was grafted onto two types of rootstocks 'Emperador' and 'Maxifort', or grown non-grafted as control. [2] Means for July yield, total yield, and fruit size were obtained by averaging data over all three plant types. [3] Different lower case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$.

3.4. Soluble Solids Content, Titratable Acidity, and Juice pH

Fruit SSC from early-to-middle and late seasons were both affected by the interaction between cultivar and plant type and shared similar trends (Tables 4 and 5). 'Sun Sugar' produced fruits with the highest SSC in both measurements of 7.0 °Brix to 7.3 °Brix in early to mid-season, and 6.3 °Brix in late season regardless of plant type. Soluble solids contents in the other five cultivars ranged from 3.8 °Brix in 'Emperador' grafted 'Early Girl' to 5.7 °Brix in 'Maxifort' grafted 'San Marzano' during early to mid-season, and from 3.7 °Brix to 5.2 °Brix in the same cultivar and plant type combinations in late season, respectively. Plant type generally resulted in similar SSC within one cultivar except that the 'Emperador' rootstock decreased SSC in 'Early Girl' compared to 'Maxifort' grafted or non-grafted plants in both measurements, and that non-grafted 'Mortgage Lifter' fruits had lower SSC than 'Maxifort' grafted plants.

Titratable acidity measured during early to middle season was affected by the interaction between cultivar and plant type (Table 4). 'Sun Sugar' produced fruit with the highest TA of 0.89% to 0.96%, higher than any other cultivar regardless of plant type. The other five cultivars generally produced similar TAs ranging from 0.55% to 0.77%, with no difference among plant types, except that 'Emperador' grafted plants produced lower TA than 'Maxifort' grafted or non-grafted 'Early Girl'. Titratable acidity in late season ranged from 0.48% to 0.67% with no difference among cultivars or plant types (Table 5). Sugar:acid ratio ranged from 6.8 to 7.7 in early to middle season, and from 7.1 to 12.0 in late season (Tables 4 and 5).

Tomato juice pH was affected by the interaction between cultivar and plant type during early- to mid-season, ranging from 3.95 to 4.34. Grafted and non-grafted plants produced similar juice pH within a cultivar (Table 4). Juice pH during late season varied among cultivars. 'Sun Sugar' and 'San Marzano' produced fruit with the highest juice pH of 4.91 and 4.62, respectively (Table 5). The cultivars 'Big Beef', 'Brandywine', 'Early Girl', and 'Mortgage Lifter' had similar juice pH of 4.37 to 4.52.

Table 4. Fruit quality variables in six tomato cultivars when grafted onto two types of rootstocks or grown non-grafted in a high tunnel during early to middle season.

		Early to Middle Season [1]				
Cultivar	**Plant Type**	**Soluble Solids Content [2] (°Brix)**	**Titratable Acidity (%)**	**Sugar: Acid Ratio [3]**	**Juice pH**	**Fruit Firmness (N)**
Big Beef	Emperador	4.2 g–i	0.62 c–e	6.8 a	4.24 a–c	7.3 b–d
	Maxifort	4.4 f–i	0.65 c–e		4.20 a–d	7.5 b–d
	Non-grafted	4.6 d–g	0.69 c–e		4.16 a–e	8.9 ab
Brandywine	Emperador	4.6 d–g	0.70 c–e	7.0 a	4.11 a–e	5.3 e
	Maxifort	4.1 g–i	0.57 de		4.24 a–c	4.8 e
	Non-grafted	4.1 g–i	0.65 c–e		4.16 a–e	4.8 e
Early Girl	Emperador	3.8 i	0.55 e	7.0 a	4.26 ab	7.7 bc
	Maxifort	5.1 b–e	0.73 cd		4.10 a–e	8.1 ab
	Non-grafted	5.1 b–e	0.74 bc		4.06 b–e	9.3 a
Mortgage Lifter	Emperador	4.6 e–h	0.69 c–e	7.1 a	4.19 a–e	6.0 de
	Maxifort	5.0 c–f	0.63 c–e		4.25 ab	5.2 e
	Non-grafted	3.9 hi	0.65 c–e		4.07 b–e	4.7 e
San Marzano	Emperador	5.5 bc	0.75 bc	7.6 a	4.18 a–e	5.7 e
	Maxifort	5.7 b	0.77 bc		4.21 a–d	5.7 e
	Non-grafted	5.3 b–d	0.69 c–e		4.34 a	6.0 de
Sun Sugar	Emperador	7.1 a	0.96 a	7.7 a	3.95 e	6.1 de
	Maxifort	7.0 a	0.93 a		3.98 c–e	6.0 de
	Non-grafted	7.3 a	0.89 ab		3.98 de	6.2 c–e
p-value	Cultivar	<0.0001	<0.0001	0.03	<0.0001	<0.0001
	Type	0.0078	0.98	0.19	0.47	0.067
	Cultivar*Type	<0.0001	<0.0001	0.055	0.014	0.0003

[1] Early to middle season fruit quality data were collected from tomato fruit harvested between 84 DAP and 105 DAP. [2] Different lower-case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$. [3] Means for sugar: acid ratio were obtained by averaging data over all three plant types.

Table 5. Fruit quality variables in six tomato cultivars when grafted onto two types of rootstocks or grown non-grafted in a high tunnel during late season.

		Late Season [1]				
Cultivar	**Plant Type**	**Soluble Solids Content [2] (°Brix)**	**Titratable Acidity [3] (%)**	**Sugar: Acid Ratio**	**Juice pH**	**Fruit Firmness (N)**
Big Beef	Emperador	4.2 cde	0.49 a	9.2 bcd	4.50 b	7.9 a
	Maxifort	4.4 b-e		8.7 bcd		
	Non-grafted	4.6 b-e		10.0 abc		
Brandywine	Emperador	4.6 b-e	0.49 a	8.7 bcd	4.52 b	5.0 c
	Maxifort	4.1 de		9.8 a-d		
	Non-grafted	4.5 b-e		9.0 bcd		
Early Girl	Emperador	3.7 e	0.54 a	8.1 cd	4.52 b	7.8 a
	Maxifort	5.0 bcd		8.6 bcd		
	Non-grafted	4.9 bcd		8.7 bcd		
Mortgage Lifter	Emperador	4.4 b-e	0.62 a	9.5 a-d	4.37 b	5.2 c
	Maxifort	4.7 bcd		11.0 ab		
	Non-grafted	4.0 de		7.1 d		
San Marzano	Emperador	5.1 bc	0.48 a	10.5 abc	4.62 ab	4.5 c
	Maxifort	5.2 b		10.4 abc		
	Non-grafted	5.1 bc		12.0 a		
Sun Sugar	Emperador	6.3 a	0.67 a	9.2 bcd	4.91 a	6.7 b
	Maxifort	6.3 a		9.0 bcd		
	Non-grafted	6.3 a		10.4 abc		
p-value	Cultivar	<0.0001	0.104	<0.0001	0.003	<0.0001
	Type	0.14	0.45	0.42	0.19	0.063
	Cultivar*Type	0.0003	0.089	0.0002	0.93	0.58

[1] Late season fruit quality data were collected from tomato fruit harvested between 124 DAP to 145 DAP. [2] Different lower-case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$. [3] Means for titratable acidity, juice pH, and fruit firmness were obtained by averaging data over all three plant types.

3.5. Fruit Firmness

Fruit firmness during early- to mid-season was affected by the interaction between cultivar and plant type (Table 4). Non-grafted 'Big Beef' and 'Early Girl', and 'Maxifort' grafted 'Early Girl' produced the firmest fruits of 8.1 to 9.3 N, higher than 'Brandywine', 'Mortgage Lifter', 'San Marzano', or 'Sun Sugar' of any plant type with similar fruit firmness ranging from 4.7 to 6.2 N. Late season fruit firmness varied among cultivars with the two hybrid cultivars 'Big Beef' and 'Early Girl' producing the firmest fruits of 7.9 N and 7.8 N, respectively (Table 5). 'Brandywine', 'Mortgage Lifter', and 'San Marzano' produced the least firm fruit of 4.5 to 5.2 N.

3.6. Fruit Color

The lightness of tomato fruit is represented by L* and was affected by the interaction between cultivar and plant type (Table 6). 'Sun Sugar' fruits, regardless of plant type, had the highest L* values of 49.9 to 50.0. 'San Marzano' of any plant type produced fruits with the lowest L* values of 36.3 to 38.8. The cultivars 'Big Beef, 'Brandywine', 'Early Girl', and 'Mortgage Lifter' had generally similar lightness in fruit color ranging from 41.2 to 45.3 regardless of plant type. Three plant types generally produced fruits with similar L* values within a cultivar, except that non-grafted 'Mortgage Lifter' fruit had higher L* value than 'Emperador' grafted plants.

The red and green coloration of tomato fruits varied among cultivars and is represented by a*, with positive values being red and negative values being green (Table 6). Fruits of 'Big Beef', 'Brandywine', 'Early Girl', 'Mortgage Lifter', and 'San Marzano' had similar a* values from 27.7 to 29.1. The yellow fruit cultivar 'Sun Sugar' had the least red coloration and lowest a* value of 13.9, lower than any other cultivar that produced red ('Big Beef' and 'Early Girl') or pink fruits ('Brandywine' and 'Mortgage Lifter'). The 'Maxifort' rootstock increased fruit red color measured as a* value compared to 'Emperador' (Table 2).

Table 6. Fruit quality parameters of six tomato cultivars when grafted onto two types of rootstocks or grown non-grafted in a high tunnel during the 2020 growing season.

Cultivar	Plant Type	Fruit Color [1,2] L*	a*	b*	Lycopene ($\mu g \cdot g^{-1}$ FW)	β-Carotene ($\mu g \cdot g^{-1}$ FW)
Big Beef	Emperador	43.5 b–d	28.3 a	31.3 b	54.3 ab	5.5 c
	Maxifort	42.9 b–d			59.3 a	
	Non-grafted	42.8 b–d			53.4 abc	
Brandywine	Emperador	44.8 bc	29.1 a	19.3 d	45.0 a–f	16.7 b
	Maxifort	43.8 b–d			27.3 d–g	
	Non-grafted	44.5 b–d			22.9 fg	
Early Girl	Emperador	41.2 de	27.7 a	29.9 b	49.6 a–d	7 d
	Maxifort	41.7 cde			59.6 a	
	Non-grafted	42.9 b–d			62.1 a	
Mortgage Lifter	Emperador	41.2 de	28.5 a	19.1 d	26.6 d–g	18.6 b
	Maxifort	43.3 b–d			30.4 c–g	
	Non-grafted	45.3 b			35 b–g	
San Marzano	Emperador	36.3 f	28.4 a	25.2 c	53.3 a–c	24.4 b
	Maxifort	37.7 f			46.6 a–e	
	Non-grafted	38.8 ef			31.2 b–g	
Sun Sugar	Emperador	50.0 a	13.9 b	43.7 a	18.5 g	45.4 a
	Maxifort	52.4 a			24.6 e–g	
	Non-grafted	49.9 a			15.7 g	
p-value	Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
	Plant type	0.0086	0.02	0.02	0.16	0.0034
	Cultivar*Type	0.0018	0.12	0.055	0.002	0.50

[1] Different lower-case letters suggest significant difference among means within a column indicated by Tukey's HSD test at $p \leq 0.05$. [2] Means for a*, b*, and β-carotene were obtained by averaging data over all three plant types.

The yellow and blue coloration of tomato fruits varied among cultivars and is represented by b*, with positive values being yellow and negative values being blue (Table 6). 'Sun Sugar' produced fruits with the most yellow coloration and highest b* value of 43.7 among all tested cultivars. Second to 'Sun Sugar', the two red fruit cultivars 'Big Beef' and 'Early Girl' had similar b* values of 31.3 and 29.9, respectively. The two pink fruit cultivars 'Brandywine' and 'Mortgage Lifter' produced the lowest b* values of 19.3 and 19.1, respectively. Among the three plant types, the 'Maxifort' rootstock increased fruit yellow color measured as b* value compared to 'Emperador' (Table 2).

3.7. Lycopene and β-Carotene Concentrations

Lycopene concentration in tomato fruit was affected by the interaction between cultivar and plant type (Table 6). 'Big Beef' and 'Early Girl' of any plant type, 'Emperador' grafted 'Brandywine' and 'San Marzano', and 'Maxifort' grafted 'San Marzano' produced fruit with comparable highest lycopene concentrations of 45 to 62.1 $\mu g \cdot g^{-1}$ FW, higher than all other treatment combinations with similar lycopene concentrations of 15.7 to 35 $\mu g \cdot g^{-1}$ FW. Grafted and non-grafted plants produced fruits with similar lycopene concentrations.

β-carotene concentration varied among tomato cultivar and plant type separately without interaction (Table 6). The yellow fruit 'Sun Sugar' produced the highest β-carotene concentration of 45.4 $\mu g \cdot g^{-1}$ FW among cultivars. Lower than 'Sun Sugar', three cultivars including 'Brandywine', 'Mortgage Lifter', and 'San Marzano' produced similar β-carotene concentrations from 16.7 to 24.4 $\mu g \cdot g^{-1}$ FW. 'Big Beef' and 'Early Girl' produced the lowest β-carotene concentrations of 5.5 and 7 $\mu g \cdot g^{-1}$ FW, respectively. Non-grafted plants produced the higher β-carotene concentration of 22.7 $\mu g \cdot g^{-1}$ FW than the 'Maxifort' rootstock of 16 $\mu g \cdot g^{-1}$ FW (Table 2).

4. Discussion

Within the experiment duration, lowest air temperature of 3.3 °C in the high tunnel occurred on 15 April 2020, compared to 2.8 °C outdoors, without frost occurrence. Daily light integral ranged from 21.8 mol·m^{-2}·d^{-1} on April 8 to 36.8 mol·m^{-2}·d^{-1} on 10 June 2020. DLI of 20 to 30 mol·m^{-2}·d^{-1} was considered sufficient for greenhouse tomatoes [36]. Daily average relative humidity in the high tunnel fluctuated from 64.4% to 83.4%, similarly to outdoor environment of 63.9% to 85.4% (Figure S2). Tomato harvests began 61 DAP on 25 May 2020, in the high tunnel, with approximately 586 GDDs accumulated from transplanting compared to 511 GDDs accumulated outdoors. This is about 3 to 4 weeks ahead of common harvest timing of tomatoes from local open field production. The high tunnel enabled early transplanting of tomato plants in March compared to typical early to mid-April transplanting in open field to avoid late spring frost and accelerated fruit ripening with elevated air temperatures, which served as the major advantages in tomato production in this study.

The last tomato harvest was on 21 August 2020, when marketable yield drastically declined compared to June or July due to excessive heat in the high tunnel. Weekly maximum air temperature from June to August were mostly above 35 °C, ranging from 34.2 °C to 39.3 °C, with weekly average air temperatures from 25.0 °C to 29.3 °C. Continuous exposure to high temperatures above 35 °C was reported to decrease fruit set, photosynthesis rate, and decrease export of photo-assimilates from leaf to fruit, especially with heat-sensitive cultivars [1]. Marketable yield in August was on average 11.1% (in 'Sun Sugar') to 17.3% (in 'Mortgage Lifter') of total marketable yield. This is one of the disadvantages of using high tunnel for warm season crop production in a subtropical climate, agreed by Frey et al. [15]. All plants were left in place with irrigation after the last fruit harvest. This accidentally enabled us to observe increased fruits set in September and October and continuous fruit production into fall. There is a possibility that if proper pest management was maintained, growers can experience extended tomato harvest until first frost, even with several weeks of yield decline in August. The potential of using high tunnels in tomato production for late season extension in a subtropical climate merits further investigation.

Among the six tested tomato cultivars, the two hybrid beefsteak cultivars 'Big Beef' and 'Early Girl' produced comparable highest marketable yields of 9.62 to 11.12 kg per fruit, with the two cultivars 'San Marzano' and 'Sun Sugar' producing the lowest marketable yields of 3.27 to 4.76 kg per plant. The low yield mainly resulted from small fruit sizes of 'San Marzano' (70.7 g per fruit) and 'Sun Sugar' (14.3 g per fruit). This was in agreement with Djidonou et al. [32] in that fruit yield was affected by both fruit number and individual fruit size. High marketable yields in 'Big Beef', 'Brandywine' and 'Mortgage Lifter' resulted from large fruit size of 261 to 386.8 g per fruit even with the lowest marketable fruit numbers. Heirloom cultivars 'Brandywine' grafted onto 'Emperador' and 'Mortgage Lifter' grafted onto 'Emperador' or 'Maxifort' produced the highest unmarketable yields with the main cause observed to be cracking due to their thin skins. In comparison, we did not observe such problem in hybrid cultivars 'Big Beef' or 'Early Girl'.

Grafting altered marketable yields of two heirloom cultivars, specifically June yield of 'Brandywine' and August yield of 'Mortgage Lifter', but not total marketable yield of any cultivar. Grafted 'Sun Sugar' plants with either rootstock type produced higher marketable fruit number than non-grafted plants. However, this was not enough to affect the total marketable yield due to small fruit size. Such results were in agreement with Lang and Nair [37] and Buller et al. [38], but contradicted with reports where grafted plant had increased marketable yields than non-grafted ones [26,32,39,40]. Our results were likely due to the lack of disease pressure when tomato plants were grown in containers with soilless substrate. One of the major advantages of vegetable grating is improved resistance to diseases inherited from the rootstock or due to improved nutrient uptake [21,37]. Use of a high tunnel may also have contributed to such results by lowering pressure of some pest problems [12,16]. To a certain degree, non-grafted seedlings performed similarly in terms of productivity to grafted plants in a containerized high tunnel production system.

Considering that grafted plants are more expensive, USD 0.78 per plant compared to non-grafted of USD 0.17 per plant, as described by Barrett et al. [29], container production with soilless substrate may serve as an alternative production system, but requires further investigation with appropriate cost–benefit analyses given that containers and soilless substrates considerably increase production cost too. The actual grafted plants used in our study cost USD 2.16 per plant when ordered from a commercial supplier, which is similar to what local growers are paying without the ability to graft their own tomato plants.

Cultivars varied in their response when grafted onto different rootstocks. For example, the 'Emperador' grafted 'Brandywine' produced decreased marketable yield compared to 'Maxifort' grafted plants but increased total unmarketable yield in 'Brandywine' compared to 'Maxifort' grafted or non-grafted plants. Non-grafted 'Mortgage Lifter' produced lower unmarketable yield than 'Maxifort' grafted plants. The effect of grafting on yield was not observed in any of the hybrid cultivar 'Big Beef', 'Early Girl', or 'Sun Sugar'. This is likely because hybrid tomato cultivars were bred to have high productivity and disease resistance [41]. It has been shown that plants' tolerance to biotic and abiotic stresses, plant nutrient uptake, fruit yield and quality were all affected by the type of scion and rootstock used [26,33,39,42–45]. Selection of appropriate rootstock and scion combinations is essential in using grafted plants to achieve certain goals in various climactic conditions and production settings. The benefits of using grafted plants should also be weighed against their high prices [15].

In the current study, grafting affected plant vegetative growth (stem diameter) and fruit quality variables including β-carotene concentration, fruit color (including L*, a*, and b*), SSC, and TA, overall or in certain cultivars. 'Emperador' resulted in higher stem diameter in tested tomato cultivars than 'Maxifort' grafted or non-grafted plants, but lower red (a* value) and yellow coloration (b* value) than 'Maxifort' grafted plants. The 'Emperador' rootstock also decreased SSC during early to mid-season and late seasons, and decreased TA during early to mid-season in 'Early Girl' than the 'Maxifort' rootstock, or non-grafted seedlings. Such negative effects on fruit quality may result from the vigorous 'Emperador' rootstock increasing plant vegetative growth and affecting partitioning of photo-assimilates into fruits. This is in agreement with Lang and Nair [37] reporting increased stem diameter and decreased SSC of grafted plants across an heirloom ('Cherokee Purple') and a hybrid ('Mountain Fresh Plus') tomato cultivar in a high tunnel in the Midwest U.S. Buller et al. [38] also reported increased stem diameter in grafted tomato plants but similar fruit quality compared to non-grafted plants. Plant growth and fruit quality can also vary among rootstock, scion type and production systems.

Lycopene and β-carotene are of the major pigments in tomato skins and serve to protect plants against excessive light by scavenging free radicals [46,47]. Besides their importance in plant metabolism, they are also important health beneficial compound source for humans due to their anti-carcinogenic effects [48]. Concentrations of lycopene and β-carotene were measured spectrophotometrically in this study. In addition, the non-destructive color measurement not only serves as a fruit quality variable and aid in assessing fruit ripeness, but can also be used to predict fruit lycopene concentrations. Color values of L*, a*, and a*/b* were correlated with lycopene concentration with good linear fits [49–51]. The use of color measurement to predict lycopene concentration may vary among tomato cultivars and production systems, and merits further investigation.

5. Conclusions

The six tested tomato cultivars varied in vegetative growth (including plant height, leaf SPAD, and stem diameter), fruit yield components, and fruit quality variables (including SSC, TA, fruit firmness, color, lycopene, and β-carotene concentrations), with 'Big Beef' and 'Early Girl' producing the highest marketable yields. Grafting affected June and August yields of two heirloom cultivars 'Brandywine' and 'Mortgage Lifter', but did not affect total marketable yield of any cultivar. Grafting, with 'Emperador' or 'Maxifort' rootstock, increased stem diameter but decreased fruit quality variables overall or in certain cultivars, likely due to the vigorous growth altering partitioning of photosynthate to fruits. Tomato cultivars varied in their response to grafting and rootstock type. The high tunnel resulted in an advancement in tomato harvest by approximately 3–4 weeks compared to typical local field production, and can be used as an effective season extension tool for the production of tomatoes in a subtropical climate.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/horticulturae7090319/s1, Figure S1: Picture of tomato plant growth and production setting at 34 DAP (A), 46 DAP (B), and 81 DAP (C) in the high tunnel; Figure S2: air temperatures (A), relative humidity (B), and daily light integral (C) in the high tunnel within the experiment durations in Starkville, Mississippi.

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