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High-Tunnel Production of Strawberries Using Black and Red Plastic Mulches

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Abstract: High tunnels are economical season extension tools for strawberry (*Fragaria* × *ananassa*) growers in nonmajor strawberry producing states in the United States (US), where grower competitiveness can be increased by off-season crop production. Six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars were transplanted on 18 November 2017 and evaluated for their growth, yield, quality, and time of fruit harvest in a high-tunnel production system in Mississippi (US Department of Agriculture (USDA) hardiness zone 8a) during one growing season from fall 2017 to spring 2018. Effects of black and red plastic mulches were compared in producing strawberries. The high tunnel raised daily air temperatures, provided frost protection, and resulted in advanced fruit harvest by 4–6 weeks compared to local field production with the first ripe fruit produced in early March. "Camino Real", "Chandler", and "Strawberry Festival" produced similar highest total marketable yields of 483 g to 559 g per plant, with "Sensation" producing the lowest marketable yield of 215 g per plant. Red mulch decreased marketable yield in March but increased it in May compared with black mulch. Mulch type did not affect plant vegetative growth or strawberry fruit quality variables including berry size, soluble solid content, total phenolic content, or total anthocyanin content.

Keywords: *Fragaria* × *ananassa*; red mulch; high tunnel; cultivar; yield; fruit quality

1. Introduction

Strawberry is one of the most consumed fruits in the United States (US), serving as an important component of a healthy diet [1]. In 2017, total strawberry production in the US was 1.6 billion tons, of which 1.3 billion pounds were fresh market strawberries, valued at $3.5 billion, second only to commercial apple (*Malus* × *domestica*) [2–5]. Strawberries are valued for their taste and basic nutrition and are rich in bioactive compounds such as anthocyanins, quercetins, and catechins, with benefits of slowing down aging, as well as preventing cardiovascular diseases, inflammation, and certain types of cancers [1,6,7]. Per capita consumption of fresh strawberries increased from 2 lbs in 1980 to 7.2 lbs in 2018 [2,8,9].

Compared to major strawberry-producing states California and Florida, producing 91% and 8% of strawberries in the US [5], strawberry production in midsouthern states accounts for 0.5% of total US production and occurs mainly on small- to medium-sized farms often diversified with other vegetable crops [4]. Locally sourced fresh strawberries are receiving increased demand through market outlets including community-supported agriculture (CSA), farmer's markets, u-pick farms, and farm stands [4]. Strawberry harvests in these states fall between February and June with peak production typically in April and May [2,4]. Strawberry harvest from field production in Mississippi often starts in late April or early May [10]. Growers use mainly June-bearing cultivars including "Camarosa", "Camino Real", "Chandler", and "Strawberry Festival" with limited use of day-neutral cultivars due to excessive heat in the south [11,12].

High tunnels are economic season-extension tools, constructed with metal frames covered with polyethylene films without automatic heating or cooling systems [13]. They can increase frost-free days, extend the growing season into early spring or late fall, and introduce considerable market edges for off-season crop production [14–16]. High tunnels are reported to advance strawberry harvest by 2–4 weeks and advance blueberry (*Vaccinium* spp.) harvests by 4–5 weeks compared to local open-field production [14,17–19]. High tunnels enable early planting and increase total yield and marketable fruit of raspberry (*Rubus idaeus*) and blackberry (*Rubus* spp.) significantly compared to field production [14,20,21]. Due to the exclusion of rain, high tunnels can reduce disease pressure and improve fruit quality in a number of crops including strawberries, blueberries, grapes (*Vitis vinifera*), and brambles [14,18,21,22]. The unit price of a high tunnel ranges from $2.25 to $5.00 per square foot, which is often justified by high market prices from off-season crops and can be recovered over 1–5 years [18,23]. There has been increasing interest from growers in the US to produce a variety of specialty crops using high tunnels [24].

Commercial strawberry production in the US mainly uses annual hill production (AHP) systems with plasticulture [25,26]. Black plastic films are extensively used in AHP systems to increase soil temperature and moisture, aid with weed control, advance fruiting, and increase crop yield and quality [27]. Plastic films of different colors other than black have also been shown to affect the yield, appearance, nutritional composition, and taste of strawberry fruit [7,28–32]. Miao et al. [7] reported that colored films, including red, yellow, green, blue, and white, affected fruit quality and bioactive compounds but had no effect on the average individual fruit weight of strawberry. Red plastic film resulted in the highest content of anthocyanins, flavonoids, phenolics, and antioxidant capacity in strawberry fruit among tested colored films [7]. Red film reflects more red and far-red light and may increase the biosynthesis of bioactive compounds [33,34]. The effect of red plastic mulch on strawberry yield and quality in a high-tunnel production system merits further investigation.

The objectives of this study were to (1) investigate the season extension effect of a high tunnel used for strawberry production in US Department of Agriculture (USDA) hardiness zone 8a, (2) compare yield and quality of different strawberry cultivars grown in a high-tunnel production system, and (3) investigate the effect of a red plastic mulch versus black plastic mulch on plant growth, fruit yield, and quality.

2. Materials and Methods

Plant cultivation and management. The experiment was conducted in a high tunnel at the R. R. Foil Plant Science Research Center of Mississippi State University (latitude 33.45° north (N), longitude 88.79° west (W); USDA hardiness zone 8a). The high tunnel measured 29.0 m long and 9.1 m wide, oriented north to south, and it was placed in full sun. The high tunnel had metal frames covered with 6 mil (0.15 mm) clear polyethylene film and had side curtains and two doors on end walls opening to 1.5 m and 3 m high, respectively (Tubular Structure, Lucedale, MS, USA). Within the experiment duration, side curtains and end doors of the high tunnel were closed when the air temperature at night was below 4.4 °C and were opened during the day with temperatures rising above 4.4 °C.

Since the heavy clay soil in the high tunnel was not suitable for growing strawberries, composted pine bark was introduced to the tunnel to build five raised beds (27.4 m long, 90 cm wide at the base, 60 cm wide at the top, and 15 cm high, spaced 1.2 m center-to-center), serving as five replications (blocks). Granular lime at a rate of 2.96 $kg{\cdot}m^{-3}$ (Soil Doctor Pelletized Lawn Lime; Oldcastle, Atlanta, GA, USA) and micronutrients (containing 6% calcium (Ca), 3% magnesium (Mg), 12% sulfur (S), 0.1% boron (B), 1% copper (Cu), 17% iron (Fe), 2.5% manganese (Mn), 0.05% molybdenum (Mo), and 1% zinc (Zn)) at a rate of 0.89 $kg{\cdot}m^{-3}$ (Micromax; ICL Specialty Fertilizers, Summerville, SC, USA) were incorporated into each raised bed before planting. A controlled release fertilizer 14N–6.1P–11.6K

(Osmocote® 14-14-14, 3–4 months; ICL Specialty Fertilizers, Summerville, SC) was incorporated into the raised beds preplanting at 5.04 kg·m^{-3}.

Six June-bearing cultivars ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Strawberry Festival", and "Sensation") and two day-neutral cultivars ("Albion" and "San Andreas") were tested in this study. Plugs of the eight selected cultivars, approximately 1 month old, were purchased from Triple J Nursery (Hayden, AL, USA). Cultivars including "Camarosa", "Chandler", and "Camino Real" were among the most used cultivars in the Southeastern states for their high yield. "Strawberry Festival" is a dominant cultivar used in Florida for its firm fruit. Other cultivars were selected on the basis of recommendations from the nursery and availability from the local source. Strawberry plugs were transplanted into the raised beds in staggered double rows 30 cm between plants and 30 cm between rows on 18 November 2017. The raised beds were covered with either a black plastic mulch (0.03 mm) or a red plastic mulch (0.03 mm) before planting (Filmtech Corp., Allentown, PA, USA). Neither film was transparent. This experiment used a split-plot design with factorial arrangement of treatments and five replications. Strawberry cultivar served as the main plot factor and was randomly distributed within a block. Within each main plot, the color of plastic mulch, red or black, served as the subplot factor. There were 10 single-plant subsamples in each subplot.

Strawberry plants were fertigated with 20N–8.7P–16.6K water-soluble fertilizer (Peters® Professional 20-20-20 General Purpose; ICL Specialty Fertilizers) at a rate of 100 ppm N through an injector (D14MZ2; Dosatron Intl. Inc., Clearwater, FL, USA) during establishment before flowers were produced. Runners were pinched regularly during the growing season. Two drip tapes (15.9 mm in diameter, 0.91 L per hour; Netafim, Tel Aviv-Yafo, Israel), spaced 30 cm apart, were laid onto each raised bed with 30 cm emitter spacing buried under the plastic mulch. All plants were drip-irrigated every day as needed. The irrigation volume, pressured at 10 psi, was adjusted during the growing season on the basis of environmental conditions and plant growth stages. A bumblebee hive containing a single colony of *Bombus impatiens* (common eastern bumblebee) (Natupol; ARBICO Organics, Tucson, AZ, USA) was introduced into the high tunnel on 18 January 2018 to facilitate pollination when blooms were observed. For pest management, acequinocyl and bifenazate were sprayed to control two spotted spider mites in May 2018.

Microenvironment in the high tunnel. Environmental conditions including air temperature, relative humidity (RH), and photosynthetically active radiation (*PAR*) were recorded in the high tunnel. A data logger (HOBO USB Micro Station H21-USB; Onset Computer Corp., Bourne, MA, USA) was installed in the center of the high tunnel. A temperature and RH sensor (HOBO S-THB-M002; Onset Computer Corp.) and a quantum sensor (HOBO S-LIA-M003; Onset Computer Corp.) were connected to the data logger to monitor air temperature, RH, and *PAR* at 15 min intervals. Daily light integral (DLI) was calculated by averaging *PAR* readings during a given day and multiplying by 0.0864 as described by Torres and Lopez [35]. Local outdoor air temperature and RH data in Starkville were obtained from the website of the USDA Natural Resources Conservation Service [36]. Growing degree days (GDDs) were calculated daily as follows: (Daily maximum temperature + daily minimum temperature)/2 − base temperature. Cumulative GDDs between certain time periods were estimated by summing daily GDDs. The base temperature used for strawberry was 3 °C [37].

Strawberry harvest. Strawberry fruit was harvested twice weekly when ripe fruit were produced. The date when each plant produced the first ripe fruit was recorded. Strawberries were culled for misshapen, disease-damaged, or insect-damaged fruits. Strawberry fruit below 10 g was also considered unmarketable yield as described by Whitaker et al. [38]. Strawberry yield, marketable and unmarketable, and the number of berries produced per plant were recorded at each harvest. Size of the strawberry fruit was estimated by single-berry weight and calculated by dividing berry yield per plant by the number of berries. Total berry yield per plant was calculated by summing the yield of all harvests during the growing season.

Plant vegetative growth. Upon completion of fruit harvest in June 2018, two plants from each plot were randomly selected to evaluate vegetative growth including plant growth index (PGI) (measured as plant height + widest width 1 + width 2 (width at the perpendicular direction to width 1)/3), number of crowns per plant, and relative leaf chlorophyll content measured as soil plant analysis development (SPAD) readings. Leaf SPAD was measured on three fully expanded leaves, at the terminal leaflet of each leaf, using a chlorophyll meter (SPAD 502 Plus; Konica Minolta, Inc., Osaka, Japan). Three readings measured from the selected leaves, one reading at each leaf, were averaged to represent relative chlorophyll content of a given plant. Aboveground shoots of two plants, randomly selected from each plot, were then destructively harvested on 26 June 2018. Each harvested shoot sample was measured for fresh weight. Shoot samples were then oven-dried at 60 °C until no change in weight was observed. The dry weight of each shoot sample was also measured.

Fruit firmness, soluble solid content (SSC), and titratable acidity (TA). Strawberry fruits from each cultivar grown with each mulch type were analyzed for quality variables including fruit firmness, SSC, and TA using fresh marketable berries. Two fruits from each plant, harvested on 7 May and 16 May, were used to measure fruit firmness. Fruit firmness, measured at the widest part of a given fruit, approximately one-third of the fruit body close to the calyx end, was assessed as the maximum penetrating force (g) during tissue breakage with a digital fruit firmness tester and a 2 mm diameter tip (FR-5120; Lutron Electronic Enterprise CO., LTD, Taipei, Taiwan). Soluble solid content was measured using one marketable fruit from each plant, when the selected fruit was sliced into halves, and juice was manually squeezed onto a digital refractometer (PR-32α; Atago U.S.A., Inc., Bellevue, WA, USA) for SSC readings. The titratable acidity of strawberry fruit was measured using an automated titrator (EasyPlus; Mettler Toledo, Columbus, OH, USA). For each replication, a composite sample containing approximately 50 g fruit (3–4 berries) from each subplot was used for TA measurement. Three subsamples were tested from each replication. 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 NaOH to an end point of pH 8.2. The titratable acidity of strawberry fruit was expressed as percentage of citric acid equivalent [39].

Juice preparation for bioactive compound analyses. To measure bioactive compounds, a composite sample containing approximately 100 g of marketable fruit from multiple plants in a certain replication was frozen at −20 °C until analysis. Approximately 50 g of frozen strawberries were then thawed at 4 °C in a refrigerator and homogenized using a laboratory blender (7010 G; Warning Commercial, Torrington, CT, USA). Homogenized samples were then centrifuged (Centrifuge 5430 R; Eppendorf, Hamburg, Germany) at 7830 rpm, 4 °C for 20 min. Supernatant was collected from each sample and used for bioactive compound analyses including total phenolic content (TPC) and total anthocyanin content (TAC).

Total Phenolic Content. Total phenolic content of strawberry fruit was determined using the Folin–Ciocalteu (FC) method described by Singleton et al. [40] with modifications. Three subsamples were tested from each replication. For each sample, 0.5 mL of strawberry juice was combined with 39.5 mL of deionized water and 2.5 mL of 10% Folin–Ciocalteu reagent (Sigma-Aldrich Co., St. Louis, MO, USA). After 6 min, 7.5 mL of 20% sodium carbonate (Sigma-Aldrich Co.) was added to the mixture and the resulting solutions were left in darkness for 2 h. The absorbance of the solution at 765 nm was measured by a spectrophotometer (Thermo Nicolet evolution 100; Thermo Scientific, Waltham, MA, USA). Results are reported as mg gallic acid equivalent per liter (mg $GAE \cdot L^{-1}$).

Total anthocyanin content. The pH differential method was used to measure total monomeric anthocyanin content in strawberry fruit with modifications [41]. Three subsamples were tested from each replication. For each sample, 300 μL of strawberry juice was added to 4.2 mL of pH 1.0 buffer (LabChem Inc., Zelienople, PA, USA) and another 300 μL of strawberry juice was added to 4.2 mL of pH 4.5 buffer (LabChem Inc.). The resulting mixtures were allowed to equilibrate at room temperature for 15 to 30 min, and then tested for absorbance at 496 nm and 700 nm using a spectrophotometer (Thermo Nicolet Evolution 100; Thermo Scientific, Waltham, MA, USA). The following formula was used to calculate the total monomeric anthocyanin content expressed as pelargonidin-3-glucoside (Pg-3-glc) equivalent: $TAC = (A \times MW \times DF \times 1000)/(\varepsilon \times 1)$, where the absorbance A was calculated as $A = (A_{496} - A_{700})_{pH1.0} - (A_{496} - A_{700})_{pH4.5}$, MW is the molecular weight of Pg-3-glc ($433.4\ g \cdot mol^{-1}$), DF is the diluting factor of the buffers, ε is the molar absorptivity of Pg-3-glc (15,600), and 1 is the path length in cm. Total anthocyanin content was reported as mg Pg-3-glc equivalent·L^{-1}, which was reported to be the predominant anthocyanin in strawberries [42].

Statistical analyses. Two-way analysis of variance (ANOVA) was performed on all tested variables. All data were analyzed using the PROC GLMMIX procedure of SAS (version 9.4; SAS Institute, Cary, NC, USA). Where indicated by ANOVA, means were separated using Tukey's honestly significant difference (HSD) test at $p < 0.05$.

3. Results

3.1. Microenvironment in the High Tunnel

Within the experiment duration from November 2017 to June 2018, daily average air temperatures in the high tunnel ranged from 3.1 °C (on 17 January 2018) to 30.7 °C (on 27 June 2018), compared to −8.33 °C to 29.44 °C outdoors on the same dates, respectively (Figure 1). Lowest daily minimum air temperatures of −12.5 °C in the high tunnel and −13.8 °C outdoors both occurred on 17 January 2018. Daily maximum air temperatures ranges from 12.1 °C to 37.5 °C in the high tunnel and from −2.8 °C to 34.4 °C outdoors. The high tunnel resulted in daily minimum, average, and maximum temperatures up to 2.1 °C, 11.4 °C, and 22.4 °C higher than the outdoor environment within the experiment duration, respectively.

Daily average RH in the high tunnel ranged from 57% (on 31 January 2018) to 96.5% (on 10 January 2018), compared to the outdoor environment ranging from 36% (on 3 January 2018) to 98% (on 10 January 2018) (Figure 2). In general, relative humidity in the high tunnel and outdoors fluctuated similarly during the growing season. The daily light integral in the high tunnel ranged from 4.52 (on 8 November 2017) to 49.73 mol·m^{-2}·day^{-1} (on 6 June 2018) within the experiment duration (Figure 3).

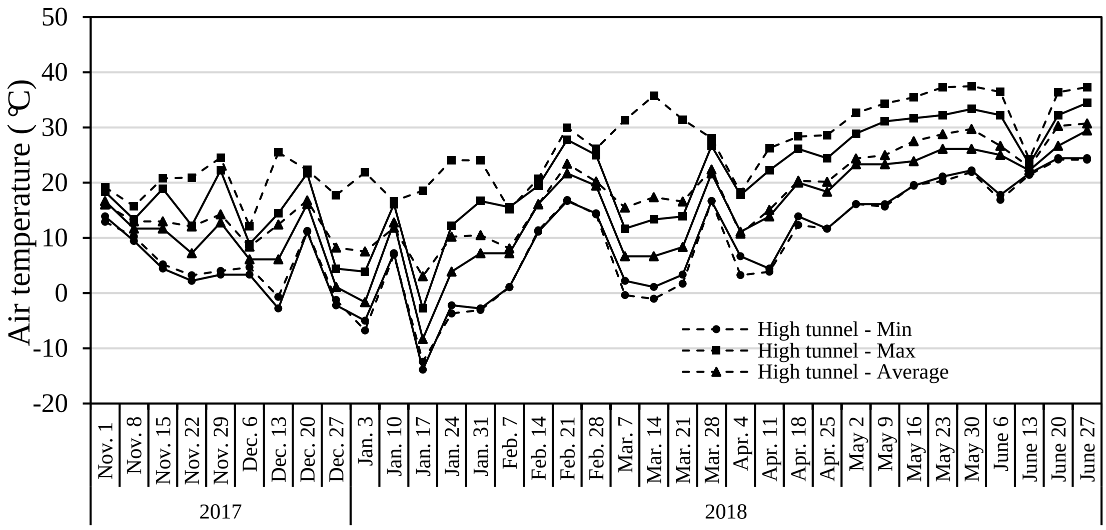

Figure 1. Daily minimum, average, and maximum air temperatures in the high tunnel and outdoors from November 2017 to June 2018 in Starkville, Mississippi. Air temperatures in the high tunnel were recorded using a temperature and relative humidity sensor (HOBO S-THB-M002; Onset Computer Corp.); local outdoor air temperature data were obtained from the United States Department of Agriculture (USDA) Natural Resources Conservation Service website.

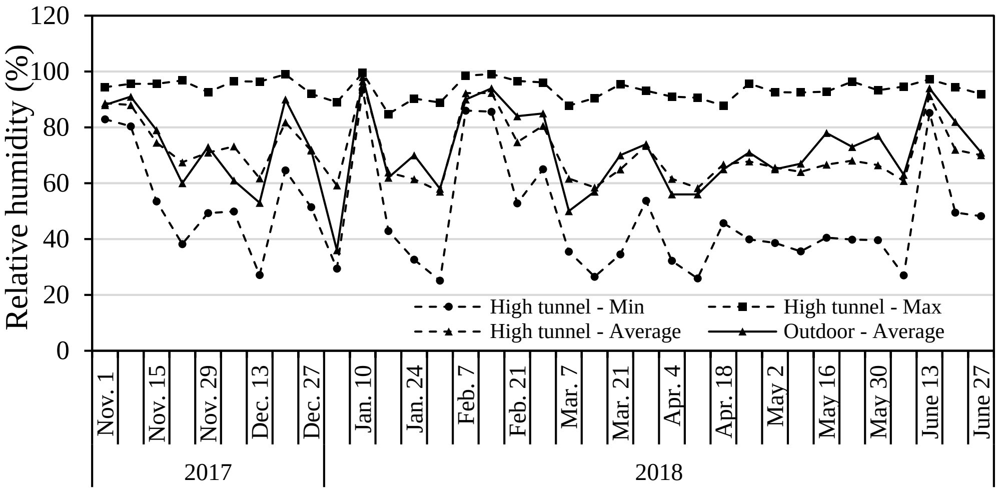

Figure 2. Daily minimum, average, and maximum relative humidity (RH) in the high tunnel and daily average RH outdoors from November 2017 to June 2018 in Starkville, Mississippi. Relative humidity in the high tunnel was recorded using a temperature and relative humidity sensor (HOBO S-THB-M002; Onset Computer Corp.); local outdoor RH data were obtained from the USDA Natural Resources Conservation Service website.

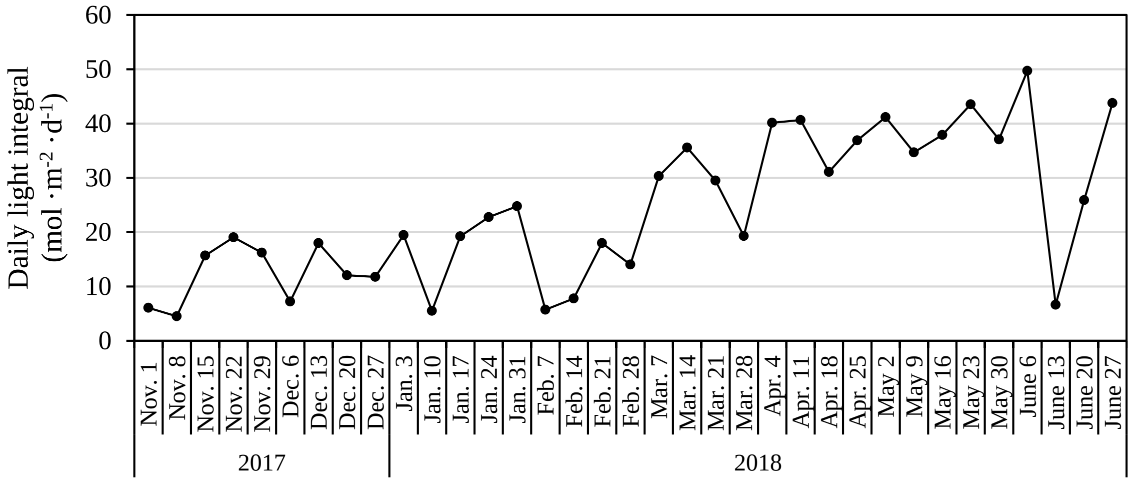

Figure 3. Daily light integral (DLI) in the high tunnel from November 2017 to June 2018 in Starkville, Mississippi. Daily light integral in the high tunnel was calculated by averaging photosynthetically active radiation (*PAR*) readings during a day and multiplying by 0.0864. *PAR* was recorded using a quantum sensor (HOBO S-LIA-M003; Onset Computer Corp.) at 15 min intervals connected to a data logger (HOBO Micro Station H21-002; Onset Computer Corp.).

3.2. Plant Vegetative Growth

The eight tested strawberry cultivars varied in their vegetative growth in terms of PGI, leaf SPAD readings, number of crowns per plant, and fresh and dry shoot weights (Table 1). Mulch type did not affect any of the tested variable mentioned above. Eight cultivars had relatively similar PGI with "San Andreas" (day-neutral) having the highest value of 34.7 cm and "Albion" (day-neutral) having the lowest of 29.9 cm (Table 2). "Albion", "Camarosa", "Camino Real", "Fronteras", and "San Andreas" had comparable leaf SPAD readings ranging from 40.9 to 43.0, higher than "Chandler", "Sensation", or "Strawberry Festival" with SPAD readings of 37.2 to 38.5. The eight cultivars had generally comparable number of crowns ranging from 3.5 to 5.4 per plant, with "Albion" having the lowest number of 3.5 per plant. Fresh and dry shoot weights of most cultivars (seven out of eight) were also similar, ranging from 72.7 g (in "Albion") to 129.6 g (in "Strawberry Festival") per plant, and from 27.3 g (in "Albion") to 44.3 g (in "Strawberry

Festival") per plant, respectively. There was no clear trend separating June-bearing from day-neutral cultivars in plant vegetative growth.

Table 1. A summary of analysis of variance for the effects of strawberry cultivar, mulch type, and the interaction between cultivar and mulch on all tested variables including plant growth index (PGI), leaf soil plant analysis development (SPAD) readings, number of crowns per plant, fresh and dry shoot weights, total marketable and unmarketable fruit yield, single-berry weight, fruit firmness, soluble solid content, titratable acidity, total phenolic content, and total anthocyanin content. GAE, gallic acid equivalent; Pg-3-glc, pelargonidin-3-glucoside.

	Plant Vegetative Growth and Total Yields ^{z}						
Effects	PGI (cm)	SPAD	Number of Crowns (per Plant)	Fresh Shoot wt. (g per Plant)	Dry Shoot wt. (g per Plant)	Total Marketable Yield (g per Plant)	Total Unmarketable Yield (g per Plant)
	p-value ^{y}						
Cultivar	<0.0001	<0.0001	0.0026	0.0079	0.0077	<0.0001	<0.0001
Mulch	0.87	0.99	0.45	0.28	0.14	0.67	0.12
Cultivar × Mulch	0.059	0.11	0.45	0.12	0.20	0.11	0.0002

	Strawberry Fruit Quality					
Effects	Single-Berry wt. (g per berry)	Fruit Firmness (g)	Soluble Solid Content (°Brix)	Titratable acidity (%)	Total Phenolic Content ^{z} (mg GAE·L^{-1})	Total Anthocyanin Content (mg Pg-3-glc equivalent·L^{-1})
	p-value					
Cultivar	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Mulch	0.57	0.30	0.25	<0.0001	0.15	0.31
Cultivar × Mulch	0.29	0.0007	0.22	<0.0001	0.44	0.45

^{z} Six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars were grown with black or red plastic mulches in a high-tunnel production system in Starkville, Mississippi from November 2017 to June 2018. ^{y} Data were analyzed by two-way analysis of variance (ANOVA) using the PROC GLMMIX procedure of SAS (version 9.4; SAS Institute, Cary, NC, USA).

Table 2. Vegetative growth of six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars grown in a high tunnel in Starkville, Mississippi from November 2017 to June 2018.

Cultivar	PGI ^{z} (cm)	SPAD	Number of Crowns (per Plant)	Fresh Shoot wt. (g per Plant)	Dry Shoot wt. (g per Plant)
Albion	29.9 c	42.9 a	3.5 b	72.7 b	27.3 b
Camarosa	32.8 abc	40.9 a	4.8 ab	101.7 ab	39.3 ab
Camino Real	31.0 bc	43.0 a	5.3 a	100.7 ab	38.6 ab
Chandler	33.0 abc	37.2 b	5.4 a	95.2 ab	37.1 ab
Fronteras	33.5 ab	42.8 a	4.8 ab	92.3 b	31.5 ab
San Andreas	34.7 a	42.5 a	4.0 ab	106.9 ab	39.6 ab
Sensation	32.7 abc	38.0 b	4.8 ab	107.6 ab	32.1 ab
Strawberry Festival	34.4 ab	38.5 b	4.8 ab	129.6 a	44.3 a
p-value ^{y}	0.0005	<0.0001	0.0026	0.0079	0.0077

^{z} Plant growth index (PGI) = (plant height + widest width 1 + width 2 (width at the perpendicular direction to width 1)/3. ^{y} Different lowercase letters within a column suggest a significant difference indicated by Tukey's honestly significant difference (HSD) test at $p \leq 0.05$.

3.3. Fruiting Time

Tested strawberry cultivars produced the earliest ripe fruit between 4 March and 14 March 2018 (Table 3). Black plastic mulch advanced ripening of strawberry fruit for 5–8 days in four cultivars, namely, "Albion", "Camarosa", "Chandler", and "Sensation". The earliest cultivars were "Camarosa" grown with black mulch and "Fronteras" grown with either mulch type, producing the first ripe fruit on 4 March and 6 March, respectively. Production of the first ripe strawberry fruit took place 106 to 116 days after transplanting and 1249 to 1374 GDDs for strawberry cultivars grown in the high tunnel.

Table 3. Date of first ripe fruit, days after transplanting (DAT), and cumulative growing degree days (GDDs) required for the first ripe fruit from planting of six June-bearing and two day-neutral strawberry cultivars grown with black or red plastic mulches in a high tunnel in Starkville, Mississippi from November 2017 to June 2018.

Cultivar	Mulch	Date of First Ripe Fruit in March 2018	DAT (d)	Cumulative GDDs from Planting [z]
Albion	Black	9th	111	1312
	Red	14th	116	1374
Camarosa	Black	4th	106	1249
	Red	12th	114	1346
Camino Real	Black	13th	115	1361
	Red	13th	115	1361
Chandler	Black	7th	109	1289
	Red	13th	115	1361
Fronteras	Black	6th	108	1279
	Red	6th	108	1279
San Andreas	Black	12th	114	1346
	Red	7th	109	1289
Sensation	Black	7th	109	1289
	Red	14th	116	1374
Strawberry Festival	Black	8th	110	1301
	Red	7th	109	1289

[z] GDDs = $(T_{daily\ max} + T_{daily\ min})/2 - T_{base}$. T_{base} = 3 °C for strawberries. GDDs were calculated on a daily basis, and cumulative GDDs during certain time periods were estimated by summing up daily GDDs.

3.4. Strawberry Yield

During the 2017 to 2018 growing season, the marketable strawberry yield of seven cultivars increased from March to May, peaked in May, decreased and ended in early June, except for "Chandler" peaking in April (Figure 4). "Camino Real" and "Strawberry Festival" produced the highest early marketable yields of 83.4 and 81.3 g per plant in March, higher than "Chandler", "Camarosa", "Fronteras", "Albion", or "Sensation", producing March yields of 34.3 g to 63.7 g per plant. In April, "Chandler" and "Strawberry Festival" produced the highest marketable yields of 213 g and 206 g per plant, respectively, higher than "Camarosa", "Fronteras", "Albion", or "Sensation", producing marketable yield of 76.5 g to 166 g per plant. Five cultivars "Camino Real", "Strawberry Festival", "Albion", "Fronteras", and "Camarosa" produced similar marketable yields in May, ranging from 216 g to 258 g per plant, higher than "Sensation" producing 94.1 g marketable yield per plant. "Sensation" had the lowest marketable yield among cultivars from March to May. "Fronteras" produced the highest marketable yield of 35.0 g per plant in June, with all other cultivars having generally comparable marketable yield ranging from 13.2 g to 25.2 g per plant. "Camino Real", "Chandler", and "Strawberry Festival" had similar highest total marketable yields of 559 g, 483 g, and 555 g per plant, respectively. "Albion", "Camarosa", "Fronteras", and "San Andreas" had comparable total marketable yield of 427 g to 475 g per plant. "Sensation" had the lowest total marketable yield of 216 g per plant.

As for unmarketable yield, "Chandler" produced significantly higher total unmarketable yield of 30.8 g per plant than any other tested cultivar, with "Camarosa" producing the second highest total unmarketable yield of 16.6 g per plant (Figure 5). During the growing season, highest unmarketable yield was produced in May in five cultivars, namely, "Camino Real", "Chandler", "Fronteras", "San Andreas", and "Strawberry Festival". Small fruits lower than 10 g per fruit were observed to be the main reason for unmarketable yields in "Chandler". "Chandler" also produced the least firm fruit among eight tested cultivars, causing unmarketable yield from mechanical damage.

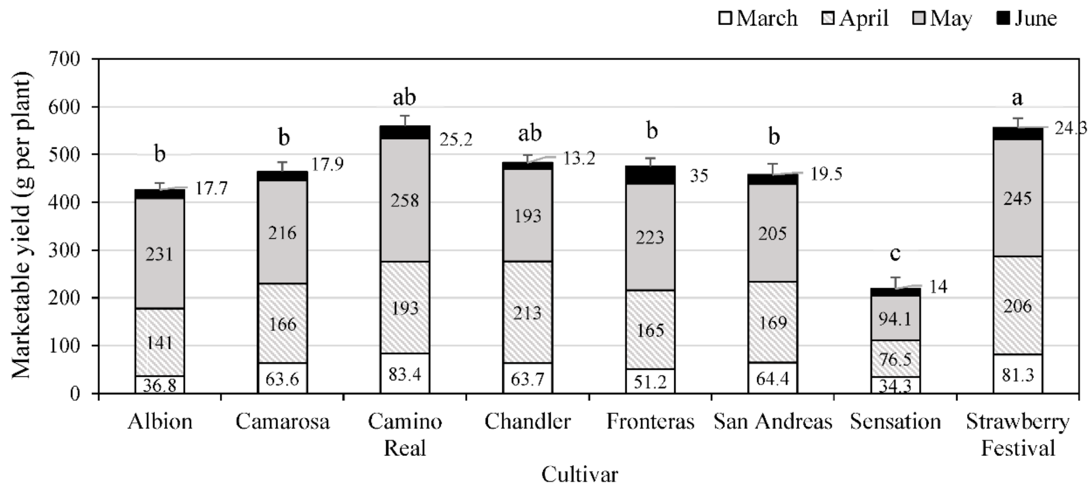

Figure 4. Monthly and total marketable yield of six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars grown with black or red plastic mulches in a high-tunnel production system in Starkville, Mississippi from November 2017 to June 2018. Different lowercase letters on top of each bar indicate a significant difference in total marketable yield among cultivars using Tukey's HSD test at $p \leq 0.05$.

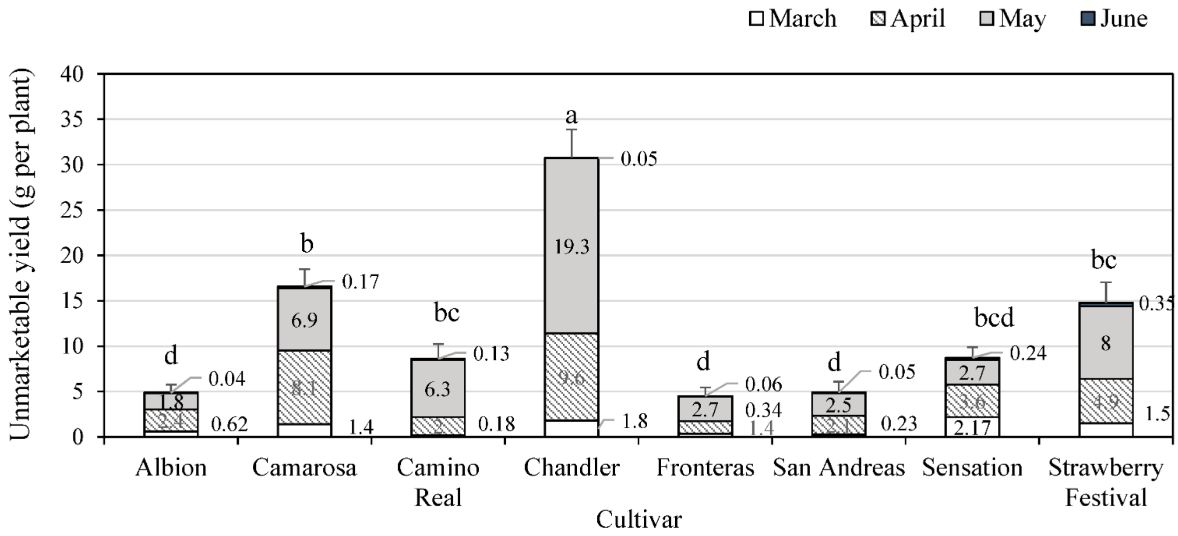

Figure 5. Monthly and total unmarketable yield of six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars grown with black or red plastic mulches in a high-tunnel production system in Starkville, Mississippi from November 2017 to June 2018. Strawberry fruits that were misshapen, disease- or insect-damaged, or below 10 g were considered unmarketable yield. Different lowercase letters on top of each bar indicate a significant difference in total unmarketable yield among cultivars using Tukey's HSD test at $p \leq 0.05$.

Compared to the red mulch, black mulch increased marketable yield by 11.2% in March, but decreased marketable yield by 9.7% in May (Table 4). Red mulch resulted in higher unmarketable yield than black mulch in March and May. There was an interaction between cultivar and mulch type in unmarketable yield in March and May, where red mulch increased unmarketable yield in "Chandler" compared with black mulch, but resulted in similar unmarketable yields in other cultivars (data not shown).

Table 4. Monthly marketable and unmarketable yields of strawberry cultivars affected by plastic mulch type grown in a high tunnel in Starkville, Mississippi from November 2017 to June 2018.

	Marketable Yield (g per Plant) [z]		**Unmarketable Yield (g per Plant)**	
Mulch	March	May	March	May
Black	63.7	202	0.7	5.3
Red	57.2	220	1.3	7.5
p-value [y]	0.03	0.018	0.018	0.037

[z] Means of a certain type of mulch was obtained by averaging data over eight tested strawberry cultivars. [y] $p \leq 0.05$ suggests a significant difference between means within a column indicated by Tukey's HSD test.

3.5. Fruit Size and Firmness

Strawberry fruit size in terms of single-berry weight of marketable fruits measured on 1 May varied among cultivars and was not affected by mulch type (Tables 1 and 5). "Albion" and "Fronteras" had the highest single-berry weight of 24.0 g and 21.9 g per berry, respectively. "Camarosa", "Camino Real", "Chandler", "San Andreas", "Sensation", and "Strawberry festival" produced comparable single-berry weights from 15.6 g to 19.7 g per berry. Strawberry fruit firmness was affected by the interaction between cultivar and mulch type (Table 1). "Albion" and "Camarosa", grown with either mulch type, "Sensation" grown with black mulch, and "Strawberry Festival" grown with red mulch produced strawberry fruit of greatest firmness ranging from 233 g to 248 g, firmer than those produced by "Camino Real", "Chandler", "Fronteras", or "San Andreas" with fruit firmness ranging from 145 g to 200 g (Figure 6A). "Chandler" produced the least firm fruit of 148 g or 145 g grown with black or red mulch, respectively. In general, the two mulch types resulted in similar fruit firmness except that black mulch increased fruit firmness in "Sensation" by 16.7% compared to the red mulch.

Table 5. Single-berry weight, fruit soluble solid content, total phenolic content, and total anthocyanin content of six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars grown in a high tunnel in Starkville, Mississippi from November 2017 to June 2018.

	Single-Berry wt [z]	**Soluble Solids Content**	**Total Phenolic Content** [y]	**Total Anthocyanin Content**
	(g per Berry)	**(°Brix)**	**(mg GAE·L^{-1})**	**(mg Pg-3-glc Equivalent·L^{-1})**
Albion	24.0 a	10.0 a	582 bc	129 cd
Camarosa	17.2 bc	8.1 cd	604 a	196 ab
Camino Real	17.1 bc	7.5 d	576 bc	202 a
Chandler	16.3 c	9.1 b	594 ab	160 bc
Fronteras	21.9 ab	8.4 c	594 ab	110 d
San Andreas	19.7 abc	8.7 bc	572 c	110 d
Sensation	19.3 abc	9.9 a	583 bc	109 d
Strawberry Festival	15.6 c	9.1 b	582 bc	134 cd
p-value [x]	<0.0001	<0.0001	<0.0001	<0.0001

[z] Single-berry weight was calculated by dividing marketable strawberry yield harvested on 1 May by the number of marketable fruit. [y] GAE stands for gallic acid equivalent; Pg-3-glc stands for pelargonidin-3-glucoside. [x] Different lowercase letters within a column suggest a significant difference indicated by Tukey's HSD test at $p \leq 0.05$.

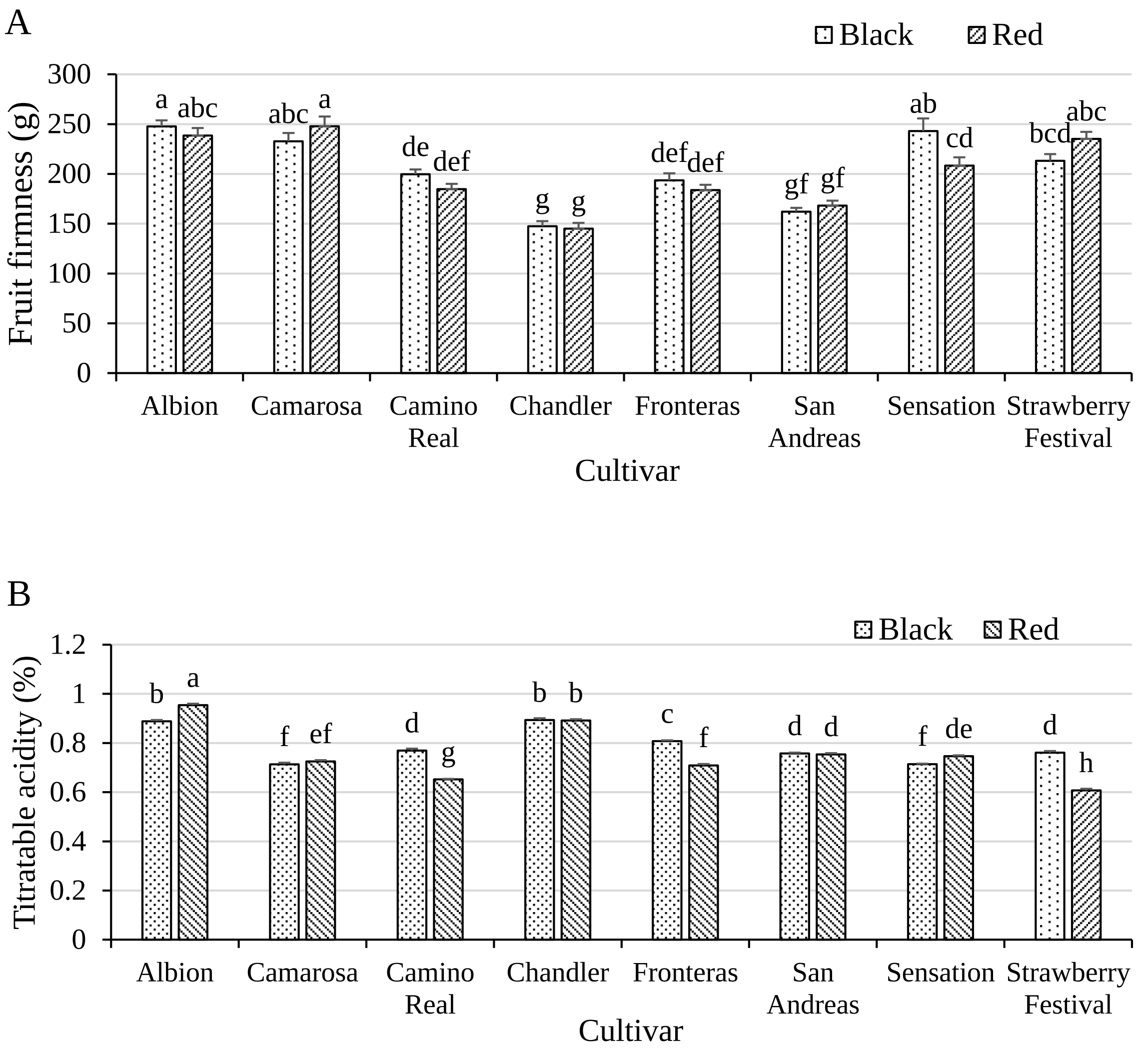

Figure 6. Strawberry fruit firmness (**A**) and titratable acidity (**B**) affected by the interaction between cultivar and mulch type grown in a high tunnel in Starkville, Mississippi from November 2017 to June 2018. Six June-bearing ("Camarosa", "Camino Real", "Chandler", "Fronteras", "Sensation", and "Strawberry Festival") and two day-neutral ("Albion" and "San Andreas") strawberry cultivars were grown with black or red plastic mulches in a high tunnel production system. Different lowercase letters on top of each bar indicate a significant difference among all treatment combinations using Tukey's HSD test at $p \leq 0.05$.

3.6. Soluble Solid Content and Titratable Acidity

Fruit SSC was affected by cultivar but not by mulch type (Table 1). "Albion" and "Sensation" produced berries with the highest SSC of 10.0°Brix and 9.9°Brix, respectively, higher than any other cultivar (Table 5). "Camarosa" and "Camino Real" produced berries of the lowest SSC of 8.1°Brix and 7.5°Brix, respectively.

Titratable acidity in strawberry fruit was affected by the interaction between cultivar and mulch type (Table 1). In general, "Albion" and "Chandler" produced fruit of higher TA than the other six cultivars, with "Albion" fruit grown with red mulch having the highest TA of 0.95% (Figure 6B). "Chandler" grown with either mulch type and "Albion" grown with black mulch produced fruits having the second highest TA of 0.89%. The other six cultivars produced strawberry fruits of 0.60% (in "Strawberry Festival" grown with red mulch) to 0.81% (in "Fronteras" grown with black mulch) TA. Red mulch resulted in 7.4% and 4.5% increased TA in "Albion" and "Sensation" compared to black mulch. However, black mulch increased TA in "Camino Real", "Fronteras", and "Strawberry Festival" by 16.9%, 13.9%, and 25.3% compared to the red mulch, respectively.

3.7. Total Phenolic Content and Total Anthocyanin Content

Bioactive compounds including TPC and TAC in strawberry fruit were affected by the main effect of cultivar, but not by mulch type (Table 1). "Camarosa", "Chandler", and "Fronteras" had comparable highest TPC ranging from 594 to 604 mg GAE·L^{-1} (Table 5). The other five cultivars including "Albion", "Camino Real", "San Andreas", "Sensation", and "Strawberry Festival" had comparable TPC of 572 to 583 mg GAE·L^{-1}. As for TAC, "Camino Real" and "Camarosa" produced strawberry fruits with the comparable highest TAC of 202 and 196 mg Pg-3-glc equivalent·L^{-1}, significantly higher than those in "Albion", "Fronteras", "San Andreas", "Sensation", or "Strawberry Festival" ranging from 109 to 134 mg Pg-3-glc equivalent·L^{-1}.

4. Discussion

The high tunnel used in this study provided frost protection by increasing the daily minimum temperature by up to 2.1 °C. Ogden and van Iersel [43] reported lower daily minimum temperature in a high tunnel compared to outdoors on a number of nights and, therefore, no frost protection from the high tunnel in Watkinsville, Georgia (USDA hardiness zone 8a), possibly due to smaller-size tunnels (12 m by 6 m) compared to ours (29.0 m by 9.1 m). Another reason could be the different management of high tunnels, whereby their high tunnels were closed on a set date and remained closed afterward [43]. However, the high tunnel used in this study was only closed when the outdoor air temperature dropped below 4.4 °C at night and was reopened when the temperature rose during the day. Such an effect of the high tunnel in increasing temperatures is similar to our previous study using high tunnels for blueberry production in the same area [18].

Requirements for GDDs in strawberry cultivars from transplanting or anthesis to fruit production can be used to predict fruit ripening grown in different climates [36,44]. Krüger et al. [36] reported strawberry cultivars required 29 to 38 days, corresponding 301 to 434 GDDs, from anthesis to fruit harvest, using 3 °C as the base temperature. Duration of fruit development was reported to be negatively related to daily average temperature. By increasing daily average air temperature up to 11.4 °C, the high tunnel accumulated approximately 430 more GDDs from transplanting in November 2017 to fruit harvest in mid-March 2018 than outdoors and advanced strawberry harvest up to 4 to 6 weeks compared to local field production, which typically starts in late April or early May [11]. The optimal growth temperature for strawberry plants ranges from 15 to 26 °C, varying among cultivars and developmental stages, with flower initiation favoring temperatures below 20 °C and vegetative growth favoring higher temperatures of approximately 25 °C [45]. The high tunnel provided a daily average air temperature of 15 to 26 °C from 14 February to 9 May 2018. With maximum air temperatures exceeding 30 °C in early May, warm temperatures in this region became the limiting factor for strawberry production further into June as agreed by Samtani et al. [4]. Early yield is more meaningful in increasing market price than extending the season into late June. Strawberry flowers were observed in the high tunnel in mid-January, but failed to develop into fruit due to freezing temperatures at the time.

Except for "Sensation", total marketable yield per plant of the seven tested cultivars were consistent with reported strawberry yields from various studies [21,46–48]. Local growers consider a satisfactory strawberry yield roughly 454 g (1 lb) per plant or above. Over the production area of the high tunnel of 264 m^2 (2850 ft^2), the total marketable yield was equivalent to 1333 g·m^{-2}. With satisfactory strawberry yield plus advanced fruit harvest by 4–6 weeks compared to local field production, the high tunnel has the potential to introduce significant profit margins for growers. The cultivar "Sensation" had survival problems in this study, mostly during plant establishment, with a mortality rate of 20% to 60% per plot, resulting in the lowest marketable yield among all tested cultivars. A possible reason might be that raised beds constructed with pine bark were relatively difficult to wet and made it challenging to satisfy water demand for strawberry plants with shallow roots. No issues of plant loss during establishment were observed with other cultivars.

The main quality components of strawberry fruits including fruit size, firmness, SSC, and TA of tested strawberry cultivars in this study were consistent with those reported by Casierra-Posada et al. [28], DeVetter et al. [49], and Gu et al. [50]. Strawberry visual qualities including size, color, and absence of damage are traditionally most important in customer preferences, especially at the initial purchase [51,52]. While fruit firmness is one of the most important attributes of strawberry post-harvest quality, customers responded positively both to "a berry that melts in your mouth" and "a firm berry that makes it home from the market" [53]. Colquhoun et al. [53] considered sweetness and complex flavors to be the most important attributes toward customers' ideal strawberry experience. With increasing demand for fresh local produce, customers are willing to pay higher prices for locally produced strawberries of better eating quality or fruits with less pesticide contamination [53,54]. Satisfactory eating quality promotes subsequent purchase of berry fruits [52], which is valued at local market outlets.

Mulch color did not affect fruit quality variables including single-berry weight and SSC, in agreement with Casierra-Posada et al. [28], who reported that red and black plastic mulches were generally comparable and produced strawberries of similar quality compared with other colored mulches, for example, silver.

Structures including mulches, plastic tunnels, and colored nets alter light intensity and quality over the plant canopy [55]. Plastic mulches of different thermal and radiation properties may, therefore, affect yield, quality, and timing of fruit production. The biosynthesis of anthocyanins in plants is promoted by a light wavelength of 640 to 670 nm, i.e., the red-light interval [34]. Red plastic mulch reflects more red and far-red light than black mulch, thereby potentially increasing anthocyanin content in strawberry fruit [33]. However, mulch type in our study did not affect TPC or TAC in the eight tested strawberry cultivars. Such results were consistent with Shiukhy et al. [55] who reported similar phenolic content in strawberry "Camarosa" grown with red or black plastic mulch in Iran. But Shiukhy et al. [55] reported increased anthocyanins in "Camarosa" fruit using red mulch compared to black mulch. Various reasons can cause the different results. For example, Shiukhy et al. [55] grew strawberries in the open field versus the high-tunnel production system used in our study. Local environment and fruit sampling method may also have affected anthocyanin content results.

In addition to an effect on anthocyanin biosynthesis in strawberry fruit, red light can affect flower initiation and soil temperature. Takeda et al. [56] reported that illuminating "Strawberry Festival" with red light resulted in a significant reduction in flowering in the fall. In the current study, red mulch reduced marketable strawberry yield early in the season in March, but increased marketable yield in May. Red mulch was reported to lower soil temperature compared to black mulch in various reports [28,30–32]. Such an effect might be negative for marketable yield in March when the daily average air temperatures were below 22.5 °C, but beneficial during May where maximum air temperatures were above 29 °C, limiting production of new flowers. Locascio et al. [32] also reported lower early yield of four strawberry cultivars using red mulch compared to black mulch when grown in Florida.

5. Conclusions

Compared to the local outdoor environment, the high tunnel used in this study increased daily minimum, average, and maximum air temperatures by up to 2.1 °C, 11.4 °C, and 22.4 °C, respectively, reduced the likelihood of frost incidence, and advanced fruit harvest by 4–6 weeks compared to typical local open field strawberry production. In the 2017 to 2018 growing season, "Camino Real", "Chandler", and "Strawberry Festival" produced similar high total marketable yields of 483 g to 559 g per plant, with "Sensation" producing the lowest total marketable yield of 216 g per plant due to plant loss in establishment. Compared to the black plastic mulch, red mulch decreased marketable yield in March, but increased marketable yield in May. Mulch type did not affect vegetative growth of strawberry plants or strawberry quality variables including single-berry weight, SSC, TPC, or TAC.

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