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Yields, Fruit Quality, and Water Use in a Jalapeno Pepper and Tomatoes under Open Field and High-tunnel Production Systems in the Texas High Plains

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***Abstract*. The Texas High Plains has a semi-arid, hot, windy climate that features high evapotranspiration (ET) demands for crop production. Irrigation is essential for vegetable production in the region, but it is constrained by depleting groundwater from the Ogallala Aquifer. High-tunnel (HT) production systems may reduce irrigation water demand and protect crops from severe weather events (e.g., hail, high wind, freezing) common to the region. The objective of this study was to compare yields, fruit quality, crop water use, and crop water use efficiency (WUE) of jalapeno pepper (*Capsicum annuum* L.) and tomatoes (*Solanum lycopersicum* L.) in HT and open field (OF) production systems. We hypothesized that the protection from dry and high winds by HT would improve yields and quality of fruits and reduce water use of peppers and tomatoes. During the 2018 and 2019 growing seasons, peppers and tomatoes were transplanted on two HT plots and two identical OF plots. Plastic mulch was used in combination with a surface drip irrigation system. Micrometeorological variables (incoming solar irradiance, air temperature, relative humidity, and wind speed) and soil physical variables (soil temperature and volumetric soil water) were measured. Air temperatures were significantly higher during the daytime, and wind speed and light intensity were significantly lower in HT compared with OF. Despite the lower light intensity, yields were greater in HT compared with OF. The fruits grown in HT did not show significant differences in chemical quality attributes, such as ascorbic acid and lycopene contents, compared with those grown in OF. Because of protection from dry, high winds, plants in HT required less total water over the growing seasons compared with OF, resulting in increased WUE. The 2018 and 2019 data showed that HT production is advantageous as compared to conventional OF production in terms of increased WUE and severe weather risk mitigation for high-value vegetable production in the Texas High Plains.**

Texas is one of the largest vegetable producers and consumers in the United States, ranking seventh in production value ($283 million) in 2017 [USDA, National Agricultural Statistics Service (NASS), 2019]. Commercial vegetable production areas in Texas are concentrated in the lower Rio Grande Valley and counties in South Texas, which comprise 19,152 ha (50.1%) of the state's total harvested area of 38,229 ha (USDA NASS, 2019). Commercial vegetable production can be found in other regions of the state, such as the High Plains, but at a much smaller scale. For instance, in 2017, the total production area of select high-value vegetables, such as peppers and tomatoes, in the Texas High Plains was less than 300 ha (USDA NASS, 2019). However, because of the irrigated production of corn, wheat, and cotton, the High Plains comprise the largest agricultural production region in the state, with 5.4 million ha (57.2%) of the state's total harvested area (USDA NASS, 2019).

The Texas High Plains has a windy, semi-arid environment; as a result, ET rates are very high. Therefore, irrigation is necessary to maximize crop yields and quality (Colaizzi et al., 2009; Evett et al., 2020). Approximately 67.7% of the state's 1.6 million ha of irrigated land is located in the High Plains area, which shows the importance of irrigation for crop production in the region (Turner et al., 2011). The principal source of irrigation in the Texas High Plains is groundwater from the Ogallala Aquifer. Because extraction from the aquifer is exceeding recharge, the water table is dropping and pumping capacity has precipitously decreased in recent years (Furnans et al., 2017). As a result, the sustainability of traditional cropping systems in the Texas High Plains, as currently practiced, is at risk, and the same situation exists for production regions in other states that depend on the Ogallala Aquifer as a source of irrigation (Bruun et al., 2017; Evett et al., 2020; Furnans et al., 2017; Scanlon et al., 2012). Therefore, regional producers are in search of means to increase revenue while using less groundwater or at least the same amount of water, and this has renewed interest in vegetable production among regional producers. Consumer trends have also raised regional growers' interests in vegetable production. Recent surveys revealed that consumers want nutritious and locally grown fresh market vegetables more than ever (Feldmann and Hamm, 2015; Yue and Tong, 2009), thereby allowing opportunities for local farmers. The concept of producing high-value vegetables is an alternative idea that could meet the growing demand for locally grown produce and optimize water use in the region. As such, how to optimize water use for growing high-value vegetables is a key research question.

Local farmers may be hesitant to adopt a new cropping system for many reasons. First, minimal research has been conducted to provide the information needed by local producers to change or diversify their crop selection. Research should provide reliable facts about vegetable production in the region to help growers make informed decisions. Second, each year in the springtime, consistent high winds up to 26.8 $m \cdot s^{-1}$ and hail threaten healthy growth of crops. These weather extremes impose severe production risks for all crops, but especially for high-value crops such as vegetables. Third, in addition to abiotic stress, there is always the threat of disease and insects, and these biological hazards to vegetables have not been adequately investigated in this region.

To protect crops from these abiotic and biotic threats, HT production systems have been suggested to ensure sustainable and stable cultivation of high-value crops in the region (Lee et al., 2018; Miles et al., 2012; Wallace et al., 2012). High tunnels, also called hoop houses, are defined as protective structures with a plastic cover that do not have active control of the internal growing environment, although one can passively control the microenvironment using management practices (e.g., heating and cooling via manual ventilation) (Lamont, 2005; Wien, 2009). This unique feature differentiates the protective environment of HTs from the controlled environment of greenhouses. Due to lower construction and operation costs than greenhouses and wide adaptability to various regions, many producers in different regions in the United States and worldwide use HTs to produce high-value crops such as leafy fruits and vegetables (Galinato and Miles, 2013), small berries (Demchak, 2009), and even fruit trees like sweet cherry (Lamont, 2009). Among these wide selections of crops, examples of the most popular and profitable crops grown in HT production systems are tomatoes, lettuce, peppers, cucumbers, and melons (Lamont, 2009). In the United States, with financial support from the USDA-Natural Resources Conservation Service, the total acreage of HT production of these crops is expected to grow. The benefits of HTs for growing high-value crops include, but are not limited to, season extension (Galinato and Miles, 2013), protection from inclement weather and pathogens (Powell et al., 2014), and increased yields and quality of crops (O'Connell et al., 2012). Using HTs to produce high-value vegetables could be a potential solution to the environmental challenges that growers face in the Texas High Plains. In particular, protection from high, dry, and hot winds during the growing season could result in significant improvements not only in yields and fruit quality but also in WUE of cropping systems.

The objective of this study was to compare yields, fruit quality, crop water use, and crop WUE of a jalapeno pepper and tomatoes (both high-value vegetables) grown in HT production systems vs. OF production systems.

Materials and Methods

A 2-year field study was conducted to compare air and soil environments, yield components, fruit quality attributes, the incidence of *Tomato spotted wilt virus* (TSWV), and water use of crops grown in HT production systems and OF production systems.

Study site description. Field experiments were conducted at the Texas A&M AgriLife Plant Stress Laboratory in Bushland, TX (lat. 35°09′N, long. 102°05′W) during the growing seasons in 2018 and 2019. The study location is described as a semi-arid (BS by the Köppen climate classification, Kottek et al., 2009), high-altitude plain (1170 m elevation above mean sea level with an average atmospheric pressure of 88.2 kPa) with a mean annual precipitation of 470 mm, 3197 h of annual solar irradiance, mean annual wind speed of 5.8 $m \cdot s^{-1}$ (NOAA National Centers for Environmental Information, 2019), and an annual Class A pan evaporation of 2600 mm (Colaizzi et al., 2017). The plant hardiness zone of the study site is 7a [USDA Agricultural Research Service (ARS), 2012]. Soil at the field research site consists of a Pullman clay loam (fine, mixed, superactive, thermic Torretic Paleustoll) with pH levels of 7.6/7.1 and 11.8/11.5 g organic matter/kg soil for HT/OF plots, respectively. Detailed texture and compositions of the soil analyzed by horizon can be found in Tolk and Evett (2012).

Experimental design and land preparation. The experimental design for the studies conducted during the 2018 and 2019 growing seasons is shown in Fig. 1. Briefly, two HT and two OF plots were used to grow a jalapeno and tomatoes during each season. Field sensors were installed in pepper and tomato beds to measure soil water content and to estimate crop WUE.

Two quonset-style HTs (GrowSpan Round Premium High Tunnel; FarmTek, Dyersvillle, IA) were used in this study. The covering material was made of 28.3-g, 0.305-mm clear woven greenhouse covering (PolyMax Clear Greenhouse Covering with added ultraviolet inhibitors) with ≈85% light transmittance. The dimensions of the HTs were 9.14 m × 29.26 m × 3.66 m (width × length × height) with 278.71 m^2 of ground area. During the study, the sidewalls of HTs were kept open at all times to dissipate the heat that built up during the day. Two OF plot areas, adjacent to the HTs and identical in size, were also used each year of the study.

Soils in the HT and OF plot areas were cultivated and formed into raised beds. In each HT and OF area, six beds 1.52 m in width and 27.47 m in length were established. Next, a surface drip irrigation system was installed with 0.381-mm drip tape (0.304-m dripper spacing with 1.02 $L \cdot h^{-1}$ flow rate) (Aqua-Traxx; Toro Micro-Irrigation, El Cajon, CA) that connected to layflats (Pro-Flat; Rivulis Irrigation Inc., San Diego, CA). Black, white, or silver polyethylene plastic mulch (thickness, 0.038 mm) covered beds in each plot (Cast Embossed Plastic; Berry Hill Irrigation Inc., Buffalo Junction, VA). These plot areas were then subdivided into four zones comprising three 1.52-m beds, 13.72 m in length. Tomatoes or peppers were transplanted in each zone, with two rows of peppers per bed or one row of tomatoes per bed. Plant spacing for each species was 0.457 m, resulting in planting densities of 2.87 and 1.44 plants/m^2 for peppers and tomatoes, respectively.

Crop seeding and transplanting. Crop management and environmental data were summarized for the 2018 and 2019 growing seasons (Tables 1 and 2). For peppers (*Capsicum annuum*), a jalapeno cultivar, J207-f (Texas A&M AgriLife, College Station, TX), was used during both years. For tomatoes (*Solanum lycopersicum*), a semi-determinate, open-pollinated-type experimental cultivar (Texas A&M AgriLife) was used in 2018, and an indeterminate F1 hybrid cultivar Hot Ty (Texas A&M AgriLife) was used in 2019. This change was made because the semi-determinate, open-pollinated cultivar proved to be poorly adapted to High Plains growing conditions. When stands were established, the tomato plants on the data rows in HTs were trellised to provide support for vine growth. Tomato plants in the OF remained nontrellised.

In 2018, peppers and tomatoes were seeded in standard 25-cm-wide × 50-cm-long 72-cell plastic trays (45.8 cm^3 per cell) (#72 Pro Trays; American Plant Products & Services Inc., Oklahoma City, OK) containing horticultural media (Mix #1; Sun Gro Horticulture, Agawam, MA) on 23 Feb. and 19 Mar. for the HT plots and OF plots, respectively. They were grown in a greenhouse at 19 to 22 °C until transplanted. In 2019, because of a thrips (*Frankliniella occidentalis* Pergande) infestation in the greenhouse, the production of transplants was outsourced to a commercial company. Peppers and tomatoes were seeded in peatmoss on 18 Feb. and 11 Mar. for the HT plots and OF plots, respectively. Seedlings were delivered to the experimental site 1 d before the scheduled transplanting dates.

In 2018, tomatoes and peppers were hand-transplanted to HTs on 23 Apr. through 25 Apr., 3 weeks earlier than the OF plots. The OF plots for tomatoes and peppers were transplanted on 7 and 8 May, respectively, using a water wheel transplanter (Model 1200; Rain-Flo Irrigation, East Earl, PA). In 2019, due to inclement weather, the transplanting schedule for the OF plots was delayed, resulting in a 6-week difference between HT and OF planting.

Soil water and temperature measurements. Volumetric soil water content was measured using a field-calibrated neutron probe (model 503DR Hydroprobe; InstoTek, Inc., Concord,

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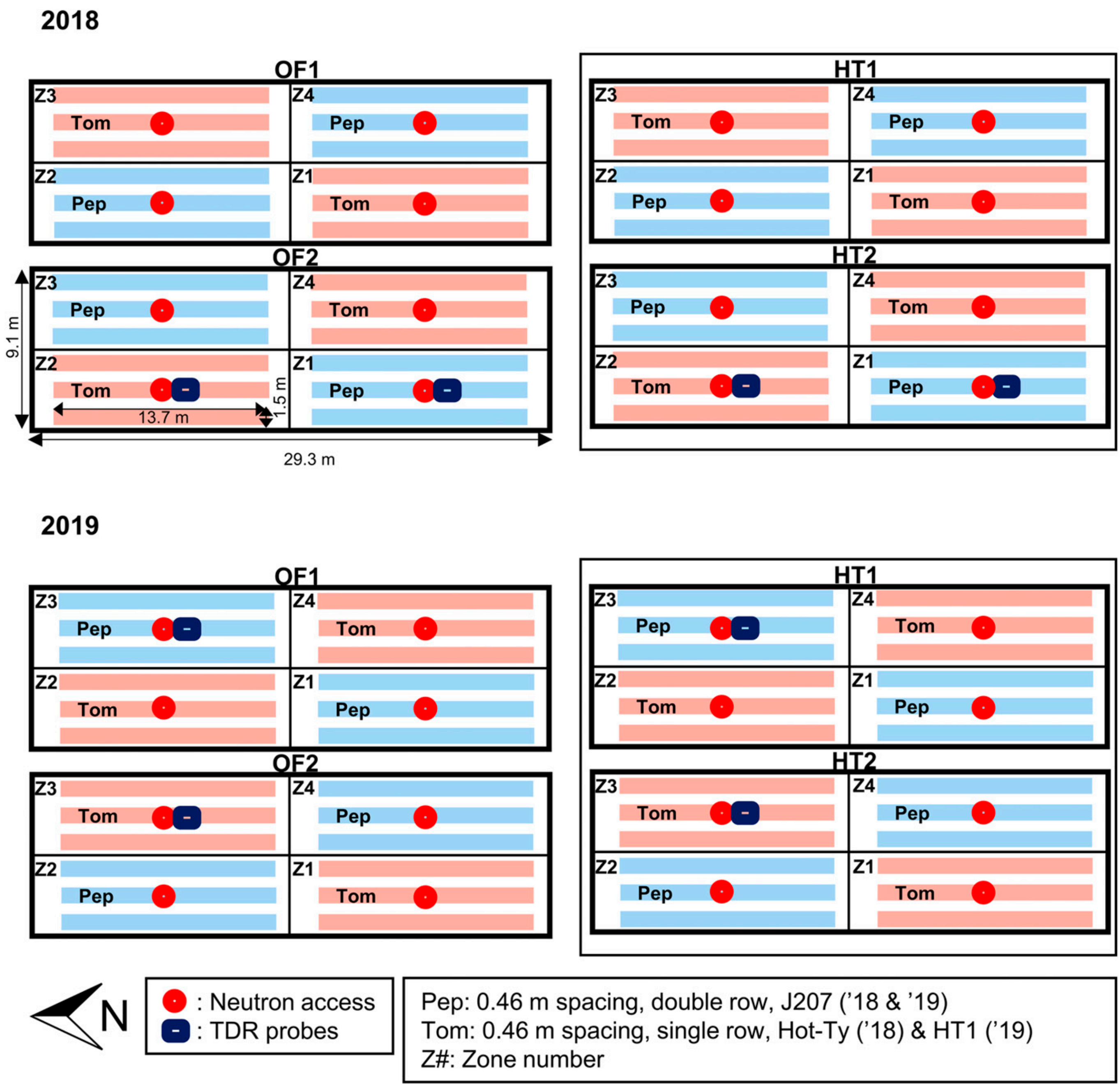

Fig. 1. Experimental designs of pepper (Pep) and tomato (Tom) beds on high-tunnel (HT) and open-field (OF) plots in the 2018 and 2019 field studies.

CA). Access tubes were installed in the middle of each plot in the center of a raised bed (Fig. 1). Access tubes were made of standard electromechanical tubing (EMT) with a diameter of 38 mm and length of 3.0 m. Soil water content was measured at 12 depths, from 0.1 m to 2.3 m, and at 20-cm increments to avoid gaps in measurement depths. The neutron probes were field-calibrated to the Pullman soil at the study location, resulting in three separate calibration equations for the Ap, Bt, and calcic soil horizons and achieving an accuracy less than 0.01 $m^3 \cdot m^{-3}$ (Evett et al., 2008). A depth-control stand was used for all calibrations and all field measurements to maintain consistent probe depths relative to the soil surface, which are required to achieve accurate measurements (<0.01 $m^3 \cdot m^{-3}$), especially at depths less than ≈30 cm (Evett et al., 2008). Neutron probe measurements were obtained weekly or biweekly from transplanting through harvest, and they were used to schedule irrigation applications.

Volumetric soil water was also measured by encapsulated probes using the time domain reflectometry (TDR) method (model TDR-315L; Acclima Inc., Meridian, ID), which also measures soil temperature. The TDR probes were installed in the center of the beds near the neutron access tubes, from a distance of ≈0.6 m to 1.2 m, and at depths of 10, 20, 30, 45, 70, and 100 cm below the soil surface (Fig. 1). The TDR probes were connected to data loggers (CR300; Campbell Scientific Inc., Logan, UT) using the SDI12 communication protocol. Soil water and soil temperature measurements were obtained every 5 min and reported as 15-min averages.

Irrigation and management practices. Irrigation in HT and OF plots was applied on a weekly basis to replenish soil water in each plot to field capacity. Plant available water/wilting point/field capacity of the soils at depths of 0.5, 1.0, and 1.5 m depths were 103/177/180, 169/188/357, and 219/295/514 mm, respectively (Tolk and Evett, 2012). The amount of irrigation applied during each event was determined by volumetric soil water profile measurements for each crop species and plot with the field-calibrated neutron probe. Tillage and crop management

Table 1. Management information and environmental characteristics of peppers during the 2018 and 2019 field seasons. The averages of environmental variables are provided with ±1 SD of the mean.

	2018		2019	
	HT	OF	HT	OF
Avg daily max air temp (°C)	38.5 ± 4.9	32.7 ± 3.8	33.7 ± 5.0	32.1 ± 4.0
Avg daily mean air temp (°C)	26.1 ± 2.8	24.6 ± 2.8	22.4 ± 4.7	24.0 ± 3.4
Avg daily min air temp (°C)	15.9 ± 3.7	16.8 ± 2.6	13.5 ± 5.2	16.1 ± 3.2
Cumulative GDD[z] (base air temp 10 °C)	2033	1774	1820	1700
Avg daily GDD (base air temp 10 °C)	16.3	14.9	13.7	14.2
Avg daily max RH (%)	79.4 ± 12.5	84.4 ± 11.1	87.4 ± 10.0	85.9 ± 11.6
Avg daily mean RH (%)	49.4 ± 12.6	55.4 ± 12.0	60.0 ± 13.7	57.4 ± 14.3
Avg daily min RH (%)	23.4 ± 9.7	28.1 ± 10.9	31.0 ± 13.7	29.7 ± 13.6
Avg daily max wind speed ($m \cdot s^{-1}$)	1.7 ± 2.9	10.2 ± 4.5	1.2 ± 0.8	7.6 ± 2.3
Avg daily mean wind speed ($m \cdot s^{-1}$)	0.5 ± 1.2	4.7 ± 4.0	0.1 ± 0.1	3.2 ± 1.0
Avg daily min wind speed ($m \cdot s^{-1}$)	0.0 ± 0.1	0.7 ± 1.2	0.0 ± 0.0	0.2 ± 0.4
Avg DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	38.0 ± 7.7	49.8 ± 8.8	29.7 ± 15.0	51.1 ± 9.5
Cumulative solar irradiance (MJ)	2315	2908	2278	2986
Avg daily ET_0[y] ($mm \cdot d^{-1}$)	6.4 ± 1.4	10.3 ± 2.8	5.3 ± 1.4	9.5 ± 2.1
Cumulative ET_0 (mm)	755	1238	709	1138
Avg daily max soil temp at 10 cm depth (°C)	29.0 ± 2.3	28.0 ± 1.7	27.2 ± 2.4	28.5 ± 2.0
Avg daily mean soil temp at 10 cm depth (°C)	27.4 ± 1.6	25.9 ± 1.4	25.0 ± 2.6	26.2 ± 1.6
Avg daily min soil temp at 10 cm depth (°C)	25.8 ± 1.5	23.7 ± 1.3	22.8 ± 2.8	24.0 ± 1.5
Cumulative GDD (base soil temp 10 °C)	1604	1489	1722	1494
Avg daily GDD (base soil temp 10 °C)	17.4	15.8	15.0	16.2
Avg soil water content ≈1 m (mm)	373.0 ± 20.2	366.2 ± 19.4	353.2 ± 21.2	332.2 ± 17.6
Precipitation (mm)	0	130	0	200
Irrigation (mm)	272	283	208	177
ET_c (mm)	258	443	264	417

[z]Growing degree days (GDDs) were calculated after transplanting peppers and tomatoes. Base temperatures for the calculations were 10 °C for both peppers (Perry et al., 1993) and tomatoes (Miles et al., 2012). $[(T_{max} + T_{min})/2 - T_{base}]$ with 0 if GDD < T_{base}, then GDD = T_{base}, where T_{max}, T_{min}, and T_{base} are maximum, minimum, and base temperatures of the day.
[y]Reference evapotranspiration (ET_0) calculated by the FAO-56 method using the weather variables.
DLI = daily light integral.

procedures, such as weed and pest control during the season, were applied on an as-needed basis and were similar to standard methods practiced by commercial farmers to promote optimum growth.

Micrometeorological measurements. Micrometeorological variables were measured in two HT (peppers and tomatoes) and two OF plots (peppers and tomatoes) during the 2018 and 2019 growing seasons. Air temperature and relative humidity (RH) were measured by sensors in a ventilated and enclosed white shelter (model EE181; Campbell Scientific Inc.). Wind speed was measured by a three-cup anemometer (model 03101-L; R.M. Young Co., Traverse City, MI). Incoming solar irradiance was measured by a silicon cell pyranometer (SP-110-SS; Apogee Instruments Inc., Logan, UT) with a reported spectral range of ≈385 to 2105 nm. All probes/sensors were installed at a height of 2 m and connected to the same data loggers used to measure soil water content and soil temperature. Measurements were sampled every 6 s and averaged to 5-min intervals.

Yield data collection and fruit quality analysis. During both years of the study, only the middle rows of the plots were used for yield, fruit quality, and water use data collection. When ≈80% fruit on the plants reached the dark green to red ripeness stage for peppers and the light red ripeness stage for tomatoes, we started harvesting. In 2018, peppers and tomatoes were harvested 124 and 131 d after transplanting (DAT), respectively, in the HT plots. In the OF plots, peppers and tomatoes were harvested 119 and 125 DAT. A 3.05-m-wide section in the middle of each crop stand of 12.19 m was chosen and the number of plants in the selected section was recorded. From these select plants, fruits were hand-collected and transferred to the laboratory and weighed. The total fruit count was determined; then, the percent marketable quality fruit was determined based on the observations of mechanical and biological defects on fruit surfaces. The marketable portion was counted and weighed separately from the total. In 2019, multiple harvests were performed for peppers and tomatoes to maximize productivity. For peppers, harvesting was conducted twice for the HT plots, at 116 and 132 DAT, but only once for the OF plots, at 119 DAT. For the indeterminate tomato cultivar, harvesting was conducted weekly from 102 to 139 DAT for the HT plots and from 105 to 126 DAT for the OF plots. The same harvest procedures and evaluation matrix were used to determine the percent marketable quality fruit.

A fruit quality analysis was conducted for peppers and tomatoes only in 2018. At 135 DAT, all peppers and tomatoes from 3.05-m lengths of rows of each crop were hand-harvested and weighed. The samples were transferred to a laboratory, sliced into small pieces, and stored in 50-mL centrifuge tubes at –80 °C until shipping.

The fruit samples were shipped to the Texas A&M University Vegetable and Fruit Improvement Center in College Station, TX, and a battery of fruit quality and phytonutrient assays were performed. For peppers, flavonoids, ascorbic acid, dehydroascorbic acid, carotenoids, carbohydrates, and capsaicinoid contents of fruits were analyzed by high-performance liquid chromatography (HPLC). For tomatoes, basic quality attributes (titrable acidity, Brix, and pH) and ascorbic and dehydroascorbic acid, carotenoids, carbohydrates, and amino acid contents of fruits that were quantified by HPLC were measured. Results were compared with reference nutrient data retrieved from the USDA FoodData Central (USDA ARS, 2019; https://fdc.nal.usda.gov/).

TSWV assessment. To assess the incidence of TSWV, we scouted for typical diagnostic symptoms of TSWV infection in peppers and tomatoes at harvest time in 2018. Plants showing symptoms (mosaic, leaf curling, or plant death) were identified and a subsample of plant tissue was collected for molecular confirmation by quantitative polymerase chain reaction testing in the laboratory.

Total RNA was extracted from the collected shoot samples using the Qiagen

Table 2. Management information and environmental characteristics of tomatoes during the 2018 and 2019 field seasons. The averages of environmental variables are provided with ±1 SD of the mean.

	2018		2019	
	HT	OF	HT	OF
Avg daily max air temp (°C)	38.3 ± 4.8	32.5 ± 3.9	33.7 ± 4.9	32.0 ± 4.0
Avg daily mean air temp (°C)	26.1 ± 2.8	24.4 ± 2.9	22.5 ± 4.7	23.9 ± 3.4
Avg daily min air temp (°C)	16.1 ± 3.7	16.7 ± 2.6	13.7 ± 5.1	16.1 ± 3.1
Cumulative GDD[z] (base air temp 10 °C)	2154	1820	1926	1787
Avg daily GDD (base air temp 10 °C)	16.4	14.5	13.8	14.1
Avg daily max RH (%)	79.4 ± 12.3	84.7 ± 11.1	87.8 ± 10.0	86.4 ± 11.5
Avg daily mean RH (%)	49.5 ± 12.4	55.9 ± 12.3	60.3 ± 13.5	58.2 ± 14.5
Avg daily min RH (%)	23.5 ± 9.5	28.6 ± 11.6	31.1 ± 13.5	30.2 ± 13.8
Avg daily max wind speed ($m \cdot s^{-1}$)	2.0 ± 3.2	10.1 ± 4.5	1.0 ± 0.9	7.6 ± 2.3
Avg daily mean wind speed ($m \cdot s^{-1}$)	0.8 ± 1.5	4.7 ± 2.4	0.1 ± 0.1	3.2 ± 1.0
Avg daily min wind speed ($m \cdot s^{-1}$)	0.1 ± 0.3	0.7 ± 1.2	0.0 ± 0.0	0.2 ± 0.4
Avg DLI ($mol \cdot m^{-2} \cdot d^{-1}$)	38.0 ± 7.6	49.3 ± 9.8	34.9 ± 9.5	50.3 ± 10.1
Cumulative solar irradiance (MJ)	2441	2976	2369	3110
Avg daily ET_0[y] ($mm \cdot d^{-1}$)	6.6 ± 1.5	10.2 ± 2.9	5.3 ± 1.4	9.3 ± 2.2
Cumulative ET_0 (mm)	821	1265	738	1187
Avg daily max soil temp at 10 cm depth (°C)	29.1 ± 1.4	30.0 ± 3.5	26.9 ± 2.9	28.2 ± 2.0
Avg daily mean soil temp at 10 cm depth (°C)	27.6 ± 1.3	26.6 ± 2.6	24.5 ± 2.8	26.2 ± 1.8
Avg daily min soil temp at 10 cm depth (°C)	25.9 ± 1.4	23.7 ± 2.0	22.1 ± 2.6	24.4 ± 1.6
Cumulative GDD (base soil temp 10 °C)	1735	1635	1742	1613
Avg daily GDD (base soil temp 10 °C)	17.5	16.9	14.5	16.3
Avg soil water content ≈1 m (mm)	336.0 ± 25.5	324.8 ± 36.6	317.3 ± 26.1	350.5 ± 19.7
Precipitation (mm)	0	130	0	213
Irrigation (mm)	288	283	241	182
ET_c (mm)	299	500	271	435

[z]Growing degree days (GDDs) were calculated after transplanting for peppers and tomatoes. Base temperatures for the calculations were 10 °C for both peppers (Perry et al., 1993) and tomatoes (Miles et al., 2012) as $[(T_{max} + T_{min})/2 - T_{base}]$ with 0 if GDD < T_{base}, then GDD = T_{base}, where T_{max}, T_{min}, and T_{base} are maximum, minimum, and base temperatures of the day.
[y]Reference evapotranspiration (ET_0) calculated by the FAO-56 method using the weather variables.
DLI = daily light integral.

RNeasy Plant Mini Kit (Qiagen, Germantown, MD) according to the manufacturer's instructions. The TSWV detection was conducted using an Applied Biosystems ViiA 7 Fast 96-well real-time polymerase chain reaction system (Applied Biosystems, Austin, TX). The TSWV primers and probe were designed with the Thermo Fisher Custom TaqMan Assay Design Tool (using sequence accession number KR080278.1) as follows: forward primer, TSWV 117F (sequence 5′–AGAGCATAATGAAGGTTATTAAGCA AAGTGA–3′); reverse primer, TSWV 245R (sequence 5′–GCCTGACCCTGATCAAGC TATC–3′); and probe, TSWV 203CP (sequence FAM 5′–CAGTGGCTCCAATCCT–3′ MGB-NFQ). The TSWV primers and probe were retrieved from ABI (assay ID APXGRRP; 20X Custom TaqMan Gene Expression Assay TSWVP) and used 1X per reaction. Each reaction mix also contained 1X TaqMan Fast Virus One-Step Master Mix (Applied Biosystems). The real-time polymerase chain reaction thermal cycling profile had the following run settings: 50 °C for 5 min and 95 °C for 20 s, followed by 40 cycles of denaturing at 95 °C for 3 s, and then annealing at 60 °C for 30 s. The threshold cycle value was set to 37 to detect TSWV.

Reference evapotranspiration comparison. Evapotranspiration of a short reference crop (ET_0) was calculated using the FAO-56 Penman-Monteith method (Allen et al., 1998). The required micrometeorological variables (air temperature, RH, solar irradiance, and wind speed) were obtained by measurements of the crops described previously.

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T + 273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \quad [1]$$

where R_n is net incoming solar irradiance at the crop surface ($MJ \cdot m^{-2} \cdot d^{-1}$), G is soil heat flux density ($MJ \cdot m^{-2} \cdot d^{-1}$), T is mean daily air temperature at a height of 2 m (°C), u_2 is wind speed at a height of 2 m ($m \cdot s^{-1}$), e_s is saturation vapor pressure (kPa), e_a is actual vapor pressure (kPa), Δ is slope vapor pressure curve ($kPa \cdot °C^{-1}$), and γ is psychrometric constant ($kPa \cdot °C^{-1}$). The ET_0 calculation is commonly combined with a crop coefficient to estimate crop evapotranspiration. However, we emphasize that the ET_0 calculation here was intended solely as a convenient means to compare the combined effects of micrometeorological variables that influence the atmospheric water demand of HT vs. OF, and not to estimate the actual crop water demand. The constants in ET_0, as defined here, require that micrometeorological variables are measured on a reference surface, including a constant surface albedo (0.23), constant crop height (0.12 m), uniform crop coverage, constant stomatal conductance, and uniform boundary layer. These conditions do not apply to seasonal crops, but variables required in Eq. [1] for nonreference conditions are not widely available. Therefore, reference conditions were assumed to assess the combined effects of micrometeorological variables in HT vs. OF, but independent of crop cover or growth stage.

Soil water balance and crop evapotranspiration. Crop evapotranspiration (ET_c) was calculated by a simple soil water balance method (Colaizzi et al., 2017; Evett et al., 2012; O'Shaughnessy et al., 2015):

$$ET_c = I + P + F + R + \Delta S \quad [2]$$

where I is irrigation ($mm \cdot d^{-1}$), P is precipitation ($mm \cdot d^{-1}$), F is net subsurface flux in/out of the control volume ($mm \cdot d^{-1}$), R is net runoff or run-on to the control volume surface ($mm \cdot d^{-1}$), and ΔS is the net change in volumetric soil water content in the control volume ($mm \cdot d^{-1}$). In many cases of agricultural lands with flat soil surfaces, F and R are assumed to be 0. The I and P were measured by totaling flow meters and rain gauges (OF only), respectively, and ΔS was measured by TDR probes (to 100 cm in 15-min intervals) and neutron probes (1.1 to 2.3 m in weekly or biweekly intervals). Minimal changes in volumetric soil water were measured below depths of ≈1.0 m. This implied that most water extraction by roots likely occurred in the top 1.0-m profile, thus supporting the assumption that F = 0 in Eq. [2].

Water use efficiency calculation. WUE is defined as the ratio of economic yield to seasonal water use:

$$WUE = \frac{YD}{\sum ET_c} \quad [3]$$

where YD is the fresh fruit yield of crop ($kg \cdot m^{-2}$) and ΣET_c is the sum of ET_c over the growing season (m) used for producing YD. WUE is commonly used to compare crop production under different conditions (i.e., HT vs. OF) regardless of the water source (i.e., irrigation, precipitation, soil water storage) (Bos, 1980; Howell, 2001). WUE has mass per volume units (i.e., kg·m^{-3}); hence, it is not a true efficiency term (i.e., no units). Therefore, sometimes "crop water productivity" is used instead of WUE, but both are defined in the same way (Evett et al., 2020).

Statistical analysis. All data collected during the study were compiled and analyzed using R version 3.2.2 (R Core Team, 2016). In addition to built-in packages, specific packages used during the analysis included 'tidyverse', 'lme4', and 'emmeans' for data compilation and organization, linear mixed-effect model fitting, and post hoc analysis of mixed-effect model results, respectively.

Because weather patterns were not consistent across the two growing seasons (2018 was drier and 2019 was wetter), we analyzed the 2018 and 2019 data separately. During each season, a linear mixed-effect model of a one-way analysis of variance (ANOVA) was constructed to analyze the statistical variations of the measured variables. Because the color of plastic mulch was not statistically significant for the measured variables, it was disregarded as a factor in the statistical models and treated as a random factor in the statistical model. Therefore, the production system as a single factor was assigned to a fixed effect and the plot number and zone number were assigned to random factors of the mixed-effect ANOVA model for yield, fruit quality, and TSWV diagnosis data. If the random effects were not significant, then they were dropped out of the model and the fixed-effect ANOVA model was used instead. For those with a significant difference in the production system effect according to the ANOVA model, within-group separation was conducted using Tukey's honestly significant difference method with $\alpha = 0.05$ as a criterion.

Results

Cultivation records. For both peppers and tomatoes, environmental conditions of the HT allowed for earlier transplanting during both 2018 and 2019 (Tables 1 and 2). Transplanting occurred 25 and 41 d earlier in the HT compared with the OF in 2018 and 2019, respectively. The growing season began in the middle of April in the HT but in the middle of May in the OF for both years. Five damaging storm events with hail occurred from 30 Apr. through 26 May 2019, and these significantly impacted the yields of OF crops. For both vegetables, the growing degree days (GDD) were greater in the HT than in the OF due to higher average maximum air temperatures in the HT and the consequent faster accumulation of the heat units during the growing season (Tables 1 and 2). These early transplanting and greater GDDs allowed earlier harvesting in the HT than in the OF (Tables 1 and 2). Harvesting occurred 20 and 44 d earlier in the HT than in the OF in 2018 and 2019, respectively. Even for peppers, second harvesting was possible in the HT in 2019.

Environmental conditions. As expected, environmental conditions differed significantly between the HT and OF. The average daily maximum air temperatures were greater in the HT than in the OF in both 2018 and 2019 (Tables 1 and 2). Differences in the average daily maximum air temperatures between the HT and OF were 5.8 and 1.6 °C in 2018 and 2019, respectively. Contrary to the maximum temperatures, the average daily minimum air temperatures were lower in the HT than in the OF in both 2018 and 2019. The average daily minimum air temperatures in the HT were 0.9 and 2.6 °C lower than those in the OF. The average daily maximum, mean, and minimum RH were all lower in 2018 and higher in 2019 in the HT than in the OF (Tables 1 and 2).

The HT significantly reduced the average wind speeds compared with the OF in both 2018 and 2019 (Tables 1 and 2). The average daily maximum wind speeds in the HT were 1.7 and 1.2 m·s^{-1}, and they were 10.2 and 7.6 m·s^{-1} in the OF, respectively, in 2018 and 2019. Incoming solar irradiance and photosynthetic light intensity were also greatly decreased in the HT compared with the OF (Tables 1 and 2). The average daily light integral (DLI) values during the experiment were 23.6% and 41.8% lower in the HT than in the OF in 2018 and 2019, respectively. Likewise, the average daily ET_0 and cumulative ET_0 both were less in the HT than in the OF in 2018 and 2019; however, they were slightly higher in 2018 than in 2019 (Tables 1 and 2). The average soil temperatures of the HT plots were slightly higher (by ≈1.2 °C on average) in 2018 but slightly lower (by ≈1.5 °C) in 2019 than in the OF plots (Tables 1 and 2).

Yield component. For peppers, the yield components showed different trends in 2018 and 2019 (Table 3). In 2018, there were no differences in any of the measured yield metrics of the two production systems. However, in 2019, total and average fruit counts were higher in the HT than in the OF. Total and single plant fruit fresh weight (FW) were also higher in the HT. Yields were 62.3% higher in the HT compared to those in the OF. The marketable fruit ratios (the ratio of the number of marketable fruits to the number of total harvested fruits) were much lower in 2019 than in 2018. Marketable pepper yields in both years were lower than the U.S. average of 29.3 Mg FW/ha, but all were higher than the state average of 6.9 Mg FW/ha.

For tomatoes, similar trends in yield components were found in both years (Table 4). In the HT, total and single plant fruit counts and FW were higher than those in the OF. The marketable fruit ratio did not differ between the two systems, but the ratio was higher in 2019 compared with 2018 in both the HT and OF. Marketable fruit counts were also higher in HT than OF, leading to higher marketable yields in both years. Marketable yields achieved in this study were significantly lower than the U.S. average of 100.1 Mg FW/ha. However, the HT production systems in both years yielded more marketable fruits than the state average of 12.1 Mg FW/ha.

Fruit quality. Most of the fruit quality attributes assayed in the present study were not significantly different for peppers and tomatoes in the HT and OF (Tables 5 and 6). When compared with the national reference

Table 3. Yield components of peppers grown in the high tunnel (HT) and open field (OF) in the 2018 and 2019 field studies. The means of each variable are reported with ± 1 SE of the means (n = 4). Reference values are retrieved from the USDA-National Agricultural Statistics Service (USDA-NASS) database and the most recent available data are presented (USDA-NASS, 2019, https://www.nass.usda.gov/Quick_Stats/). Blank field (—) indicates that reference values are not available on USDA-NASS.

Yr	System	No. of plants (no./plot)	Fruit count total (no./plot)	Fruit count (no./plant)	Fruit FW total (kg/plot)	Fruit FW (kg/plant)	Fruit FW (g/fruit)	Yield (Mg/ha)
2018	HT	11 ± 0 a[z]	854 ± 99 a	78 ± 9 a	17.3 ± 1.8 a	1.57 ± 0.17 a	20.5 ± 1.9 a	37.2 ± 3.8 a
	OF	11 ± 0 a	955 ± 84 a	87 ± 8 a	16.2 ± 0.8 a	1.48 ± 0.07 a	17.3 ± 1.4 a	34.9 ± 1.8 a
2019	HT	14 ± 0 b	1459 ± 83 a	106 ± 7 a	18.6 ± 1.0 a	1.35 ± 0.09 a	12.8 ± 0.7 b	40.1 ± 2.2 a
	OF	15 ± 0 a	558 ± 7 b	39 ± 0 b	11.5 ± 0.3 b	0.79 ± 0.02 b	20.6 ± 0.4 a	24.7 ± 0.7 b
Reference		—	—	—	—	—	—	—
Yr	**System**	**Market ratio (%)**	**Market fruit count (no./plot)**	**Market fruit count (no./plant)**	**Market fruit FW total (kg/plot)**	**Market fruit FW per plant (kg/plant)**	**Market fruit FW per fruit (g/fruit)**	**Market yield (Mg/ha)**
2018	HT	85.0 ± 3.0 a	727 ± 87 a	66 ± 8 a	15.9 ± 1.6 a	1.45 ± 0.14 a	22.3 ± 2.6 a	17.3 ± 1.8 a
	OF	90.0 ± 2.0 a	865 ± 90 a	79 ± 9 a	14.2 ± 1.1 a	1.29 ± 0.11 a	16.7 ± 1.1 a	16.2 ± 0.8 a
2019	HT	32.8 ± 5.3 b	478 ± 82 a	35 ± 6 a	9.5 ± 2.0 a	0.69 ± 0.15 a	19.5 ± 0.7 b	20.4 ± 4.3 a
	OF	67.9 ± 4.0 a	379 ± 22 a	26 ± 2 a	8.5 ± 0.7 a	0.59 ± 0.05 a	22.5 ± 0.4 a	18.4 ± 1.4 a
Reference		—	—	—	—	—	—	29.3/6.9 (United States/Texas)

[z]Different letters indicate significant difference between treatment groups separated by Tukey's honestly significant difference post hoc analysis at $\alpha = 0.05$.

values, the pepper and tomato fruits produced in 2018 had acceptable standard quality. However, there were notable exceptions. For peppers, dehydroascorbic acid and cryptoxanthin contents were lower in the fruits grown in the HT than those in the OF (Table 5). For peppers in the HT and OF, the total ascorbic acid content was lower than the national reference of 1186 μg/g FW, but the β-carotene content was greater than the reference of 5.61 μg/g FW (Table 5). Furthermore, a few amino acids, γ-aminobutyric acid, isoleucine, and leucine, were greater in HT fruits (Table 6).

For tomatoes, the quantified carotenoids 5, 7, 13, and 15-cis-lycopene and translycopene,

Table 4. Yield components of tomato fruits grown in the high tunnel (HT) and open field (OF) in the 2018 and 2019 field studies. The means of each variable are reported with ± 1 SE of the means (n = 4). Reference values are retrieved from the USDA-National Agricultural Statistics Service (USDA-NASS) database and the most recent available data are presented (USDA-NASS, 2019, https://www.nass.usda.gov/Quick_Stats/). Blank field (—) indicates that reference values are not available on USDA-NASS.

Yr	System	No. of plants (no./plot)	Fruit count total (no./plot)	Fruit count (no./plant)	Fruit FW total (kg/plot)	Fruit FW (kg/plant)	Fruit FW (g/fruit)	Yield (Mg/ha)
2018	HT	7 ± 1 a[z]	106 ± 10 a	17 ± 2 a	12.2 ± 1.7 a	1.92 ± 0.31 a	114.0 ± 6.7 a	26.3 ± 3.7 a
	OF	6 ± 0 a	56 ± 9 b	9 ± 1 b	5.2 ± 0.6 b	0.86 ± 0.10 b	95.9 ± 12.5 b	11.2 ± 1.4 b
2019	HT	7 ± 0 a	366 ± 16 a	54 ± 4 a	41.0 ± 2.6 a	6.05 ± 0.48 a	112.0 ± 3.9 a	88.2 ± 5.5 a
	OF	7 ± 0 a	145 ± 24 b	21 ± 4 b	15.9 ± 2.1 b	2.25 ± 0.33 b	112.0 ± 5.8 a	34.3 ± 4.6 b
Reference		—	—	—	—	—	—	—
Yr	System	Market ratio (%)	Market fruit count (no./plot)	Market fruit count (no./plant)	Market fruit FW total (kg/plot)	Market fruit FW per plant (kg/plant)	Market fruit FW per fruit (g/fruit)	Market yield (Mg/ha)
2018	HT	29.1 ± 4.1 a	30 ± 2 a	5 ± 1 a	4.3 ± 0.3 a	0.69 ± 0.10 a	146.0 ± 8.3 a	15.8 ± 2.2 a
	OF	27.9 ± 6.0 a	15 ± 3 b	3 ± 1 a	2.1 ± 0.4 b	0.35 ± 0.07 a	140.0 ± 4.8 a	6.7 ± 0.8 b
2019	HT	41.5 ± 3.6 a	154 ± 20 a	23 ± 3 a	19.9 ± 2.0 a	2.95 ± 0.36 a	131.0 ± 4.8 a	42.8 ± 4.2 a
	OF	36.2 ± 4.4 a	51 ± 8 b	7 ± 1 b	6.9 ± 1.3 b	0.98 ± 0.19 b	133.0 ± 8.4 a	14.8 ± 2.8 b
Reference		—	—	—	—	—	—	100.1/12.1 (United States/Texas)

[z]Different letters indicate significant difference between treatment groups separated by Tukey's honestly significant difference post hoc analysis at α = 0.05 level.

Table 5. Ascorbic acid, carotenoid, and carbohydrate compositions of pepper and tomato fruits grown in the high-tunnel (HT) and open-field (OF) plots in the 2018 field study. The means of each compound are reported with ± 1 SE of the means (n = 4). Reference values are retrieved from the USDA-FoodData Central database (USDA ARS, 2019, https://fdc.nal.usda.gov/). Blank field (—) indicates that either compounds were not analyzed, or reference values are not available on USDA-FDC.

Species	System	Asc (μg/g FW)	De-Asc (μg/g FW)	Total-Asc (μg/g FW)	β-Car (μg/g FW)	5-*cis*-Lyc (μg/g FW)	7-*cis*-Lyc (μg/g FW)	13-*cis*-Lyc (μg/g FW)	15-*cis*-Lyc (μg/g FW)	*trans*-Lyc (μg/g FW)
Pepper	HT	369 ± 41 a[z]	336 ± 30 b	705 ± 53 a	9.5 ± 1.4 a	—	—	—	—	—
	OF	220 ± 61 a	521 ± 42 a	742 ± 75 a	11.1 ± 0.8 a	—	—	—	—	—
	Reference	—	—	1186	5.6	—	—	—	—	—
Tomato	HT	186 ± 13 a	63 ± 17 a	250 ± 23 a	3.2 ± 0.2 a	3.41 ± 0.03 b	2.21 ± 0.22 b	1.79 ± 0.10 b	0.42 ± 0.02 b	79.3 ± 4.0 b
	OF	183 ± 5 a	66 ± 1 a	249 ± 6 a	3.9 ± 0.0 a	5.10 ± 0.20 a	4.48 ± 0.29 a	2.64 ± 0.09 a	0.74 ± 0.01 a	117.0 ± 6.9 a
	Reference	—	—	137	4.5	—	—	—	—	25.7
Species	System	Cry (μg/g FW)	Glc (mg/g FW)	Frc (mg/g FW)	Suc (mg/g FW)	Sum (mg/g FW)	SSC (°Brix)	Acidity (pH)	Acidity (g/L)	
Pepper	HT	3.51 ± 0.35 b	—	—	—	—	—	—	—	
	OF	5.08 ± 0.11 a	—	—	—	—	—	—	—	
	Reference	1.05	—	—	—	—	—	—	—	
Tomato	HT	—	5.63 ± 1.61 a	13.1 ± 1.8 a	4.85 ± 0.95 a	23.6 ± 4.1 a	5.83 ± 0.38 a	4.79 ± 0.04 a	3.91 ± 0.08 a	
	OF	—	5.76 ± 0.63 a	13.0 ± 0.7 a	5.52 ± 0.69 a	24.3 ± 1.1 a	6.56 ± 0.27 a	4.77 ± 0.04 a	4.66 ± 0.44 a	
	Reference	—	12.5	13.7	0	26.2	—	—	—	

[z]Different letters indicate significant difference between treatment groups separated by Tukey's honestly significant difference post hoc analysis at α = 0.05.
Asc = ascorbic acid; De-Asc = de-hydro ascorbic acid; Total-Asc = total ascorbic acid; β-Car = β-carotene; *cis*-Lyc = *cis*-lycopene; *trans*-Lyc = *trans*-lycopene; Cry = cryptoxanthin; Glc = glucose; Frc = fructose; Suc = sucrose; Sum = total soluble sugars by Glc + Frc + Suc; SSC = soluble sugar content.

Table 6. Amino acid composition of pepper and tomato fruits grown in the high-tunnel (HT) and open-field (OF) plots in the 2018 field study. The means of each compound are reported with ± 1 SE of the means (n = 4). Reference values are retrieved from the USDA-FoodData Central database (USDA ARS, 2019, https://fdc.nal.usda.gov/). Blank field (—) indicates that either compounds were not analyzed, or reference values are not available on USDA-FDC.

Species	System	Ala (μg/g FW)	Asn (μg/g FW)	Asp (μg/g FW)	β-Ala (μg/g FW)	GABA (μg/g FW)	Glu (μg/g FW)	H-Pro (μg/g FW)	Ile (μg/g FW)
Pepper	HT	—	3993 ± 405 a[z]	888 ± 128 a	244 ± 56 a	833 ± 112 a	287 ± 36 a	—	43.6 ± 6.1 a
	OF	—	3639 ± 497 a	571 ± 78.6 a	197 ± 22 a	464 ± 60 b	259 ± 58 a	—	23.3 ± 4.3 b
	Reference	—	—	—	—	—	—	—	—
Tomato	HT	48.8 ± 5.7 a	885 ± 120 a	2422 ± 221 a	62 ± 8 a	704 ± 91 a	649 ± 63 b	499 ± 61 a	15.5 ± 3.5 a
	OF	43.8 ± 4.2 a	1142 ± 161 a	2780 ± 305 a	76 ± 5 a	793 ± 50 a	875 ± 83 a	543 ± 67 a	21.9 ± 2.3 a
	Reference	270.0	—	1350	—	—	4310	—	180
Species	System	Leu (μg/g FW)	Met (μg/g FW)	Phe (μg/g FW)	Pro (μg/g FW)	Ser (μg/g FW)	Thr (μg/g FW)	Trp (μg/g FW)	Val (μg/g FW)
Pepper	HT	100 ± 16 a	36.7 ± 5.5 a	147 ± 16 a	158 ± 23 a	99.6 ± 14.6 a	198 ± 21 a	38.9 ± 6.4 a	392 ± 49 a
	OF	49 ± 8 b	21.4 ± 3.9 a	114 ± 20 a	194 ± 30 a	81.0 ± 11.4 a	139 ± 20 a	27.3 ± 4.9 a	218 ± 34 b
	Reference	—	—	—	—	—	—	—	—
Tomato	HT	18 ± 3 a	7.3 ± 1.1 a	82 ± 9 b	43 ± 17 a	56.1 ± 2.2 a	64 ± 6 b	16.5 ± 0.6 a	45 ± 7 a
	OF	24 ± 3 a	8.6 ± 1.2 a	111 ± 8 a	73 ± 20 a	58.6 ± 4.8 a	91 ± 10 a	20.4 ± 2.4 a	50 ± 7 a
	Reference	250	60.0	270	150	260	270	60	80

[z]Different letters indicate significant difference between treatment groups separated by Tukey's honestly significant difference post hoc analysis at α = 0.05 level.
Ala = alanine; Asn = asparagine; Asp = aspartic acid; β-Ala = β-alanine; GABA = *gamma*-aminobutyric acid; Glu = glutamine; H-Pro = hydroxy proline; Ile = isoleucine; Leu = leucine; Met = methionine; Phe = phenylalanine; Pro = proline; Ser = serine; Thr = threonine; Trp = tryptophan; Val = valine.

but not β-carotene, were reduced in the HT tomatoes (Table 5). The translycopene levels of the HT and OF tomatoes were both higher than the reference level of 25.7 μg/g FW.

The total ascorbic acid content was ≈2-fold in both the HT and OF compared with the national reference of 137 μg/g FW (Table 5). The amino acid contents of the tomatoes were lower than the reference ranges on average, except aspartic acid (Table 6). Significantly lower contents were found in glutamine, phenylalanine, and threonine in the HT tomatoes compared with the OF tomatoes.

TSWV diagnosis. Approximately 30% of the symptomatic HT tomato and pepper plants were infected by TSWV (Fig. 2). This was significantly lower than the nearly 90% TSWV infection rate in the OF production.

Water use and water use efficiency. Cumulative precipitation was lower in 2018 compared with 2019 (Tables 1 and 2). As a result, to meet the water requirements of the crops, cumulative irrigation was greater in HT than in OF, by 31 and 59 mm for peppers and tomatoes, respectively, in the 2019 season. However, cumulative irrigation in 2018 did not differ between the HT and the OF plots.

Total water use for peppers and tomatoes, calculated by ET_c, was significantly lower in the HT compared with that in the OF for both seasons (Tables 1 and 2). In 2018, in the HT, 46.4% and 51.4% less water was used for producing peppers and tomatoes, respectively. This led to increases in WUE by 98.6% and 382% for peppers and tomatoes, respectively (Fig. 3). In 2019, we observed similar patterns of decreased water use and increased WUE, but the increase in WUE for peppers was not significant (Fig. 3). Approximately 36.6% and 37.7% less water was used for peppers and tomatoes, respectively. The subsequent increases in WUE were 75.9% and 364.7% for peppers and tomatoes, respectively.

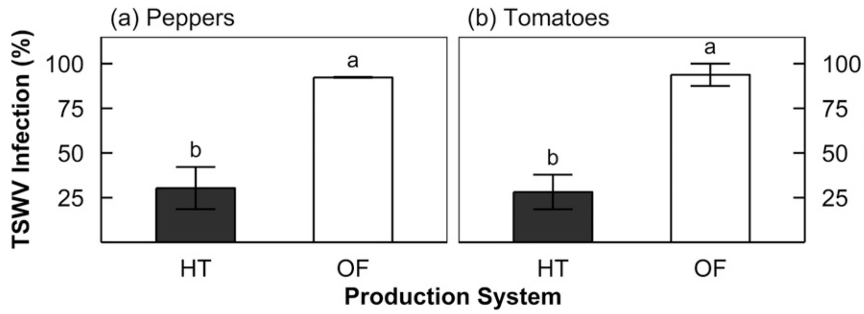

Fig. 2. Incidence of *Tomato spotted wilt virus* (TSWV) detected by quantitative polymerase chain reaction (qPCR) testing of pepper (**A**) and tomato (**B**) fruits grown in the high tunnel (HT; black bars) and open field (OF; white bars) in the 2018 field study. Bars are the mean responses of four replications with error bars indicating ±1 SE of the means (n = 4). Different letters indicate significant differences between treatment groups separated by Tukey's honestly significant difference post hoc analysis at α = 0.05.

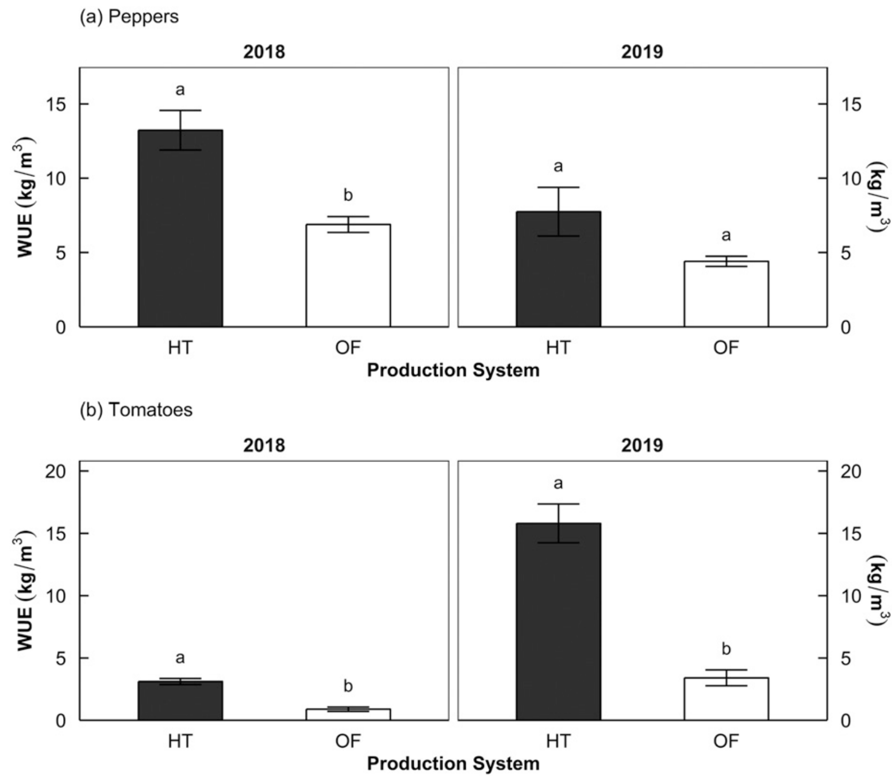

Fig. 3. Water-use efficiency (WUE) for productivity of fresh market fruit yields divided by water used by pepper (**A**) and tomato (**B**) grown in the high tunnel (HT; black bars) and open field (OF; white bars) in the 2018 (left panels) and 2019 (right panels) field study. Bars are the mean responses of four replications with error bars indicating ±1 SE of the means (n = 4). Different letters indicate significant differences between treatment groups separated by Tukey's honestly significant difference post hoc analysis at α = 0.05.

Discussion

Season extension, increased yields, and decreased disease incidence are the principal benefits of HT production systems that have been widely and extensively documented across different climatic conditions and different crops (Demchak, 2009; Galinato and Miles, 2013; Lamont, 2009; O'Connell et al., 2012; Powell et al., 2014). In the present study, we documented another benefit of HT production systems: less water use for the production of peppers and tomatoes in a semi-arid, windy climate. The weather variation observed during the 2 years allowed assessment of the consistency of the effects of the HT on the measured metrics in this climate. Most of the major fruit quality chemical attributes were not significantly affected by HT production systems, which is of interest to regional producers and consumers.

The HT production system provides a unique, protective microclimate that depends on OF weather conditions and can be modified with cultural and management practices (Wien, 2009). Despite a varying degree of modifications, general environmental characteristics of HTs can be summarized as higher air and soil temperatures and lower RH, wind speeds, and incoming solar irradiance, all of which affect the production of the crops in HTs (Heckler, 2017). Therefore, documenting region-specific or season-specific variations in the microenvironment of HTs and assessing the effects of the microenvironmental modifications are critical for making conclusions regarding the adaptability, feasibility, and optimization of HT production systems in a certain region.

In this study, transplanting in the HT was possible ≈3 to 6 weeks earlier compared with that in the OF for the 2018 and 2019 seasons, respectively (Tables 1 and 2). In both years of the study, HTs provided protection from hail and damaging high winds in early April. Such extreme weather events are common in early spring in the Texas High Plains and represent an annual threat. Therefore, the reduced risk of crop failure conferred by HTs could greatly benefit those who want to grow high-return crops. Furthermore, the increased air temperature during the early spring months in HTs proved beneficial to the establishment of transplants.

The earlier start of the growing season in the HT compared with the OF resulted in earlier harvesting of the crops (Tables 1 and 2). Similar results were observed (1–3 weeks earlier planting and harvesting) in another study of an open-pollinated cultivar tomato in a sub-humid area in North Carolina (O'Connell et al., 2012), but the extent of the season extension effects observed in the present study (up to 6 weeks in 2019) was greater in another region. It is clear that earlier harvesting of crops in the HT compared with the OF has the potential to increase premiums for producers (Bruce et al., 2019; Galinato and Miles, 2013). However, it should be noted that the benefits of season extension will vary based on year-by-year climate variations and crop species.

The reduced daily minimum temperatures during the seasons found in our study (Tables 1 and 2) are consistent with those observed by Ogden and van Iersel (2009) and Wien (2009), although Heckler (2017) reported that minimum daily temperatures were greater in HT compared with OF. Ventilation through the side vents, which remained open during the experiment, may have caused the faster decrease in daily minimum air temperatures in HTs, thus mitigating the accumulation of long-wave heat during the daytime in the HTs. Higher maximum temperatures in the HT compared with the OF in the daytime, followed by lower minimum temperatures at night, are typical in the High Plains and agree with Wallace et al. (2012), who conducted studies in the same region. In contrast to the air temperatures in the HT, with ≈16 to 22 °C of diurnal fluctuations, soil temperatures were rather stable, with ≈0.8 to 1.5 °C diurnal fluctuations (Tables 1 and 2). Studies have also demonstrated increased soil temperatures in HT (Heckler, 2017; Wien, 2009).

The HT production systems did not change the yields of peppers, but they did increase the yields of tomatoes (Tables 3 and 4). Trellising in HTs might have improved the penetration of the sunlight in the low parts of canopy layers of tomatoes in HTs, which would increase overall photosynthesis and biomass gain of the plants. Also, for tomatoes, more fruits were set per plant in the HT. This led to an increase in fruit FW per plant, although the average FW per fruit did not differ. As a consequence, tomatoes in the HT yielded more marketable fresh fruits and, accordingly, higher marketable yield by 134.7% compared with that in the OF. A significant unmarketable loss of tomatoes was recorded in 2018 and 2019 in both the HT and OF. In 2018, many of the tomato fruits were affected by a physiological disorder called cat-facing, which is common to an open-pollinated type of tomato cultivar (Gleason and Edmunds, 2005) and to tomatoes grown in an arid climate with large diurnal temperature variations (Armbrust and Retta, 2000; Masarirambi et al., 2009). Considering that tomatoes were planted in early Apr. 2018, low temperatures at the anthesis stage, a primary reason for cat-facing, may have caused the disorder. Cracking was also a common physiological defect on many tomatoes, including our 2018 selection. Temperature extremes between daytime and nighttime, which are common to the region, may have triggered fruit cracking (Peet, 1992). Because some tomato cultivars, including our 2018 semi-determinate, open-pollinated selection, seem to be genetically predisposed to these defects, careful attention is needed when selecting cultivars (O'Connell et al., 2012). The selection of the tomato cultivar hugely impacted the yield. The indeterminate cultivar used in 2019 produced multiple harvests, which increased the overall and marketable yields of tomatoes.

The dry, warm climate of the Texas High Plains is highly conducive to widespread distribution of thrips in commercially important crops (Dintenfass et al., 1987; Doederlein and Sites, 1993). The potential damage from thrips includes the transmission of TSWV that may cause stunted growth of peppers and tomatoes and even plant death. The results of our TSWV survey provided evidence of reduced biotic disease pressure caused by the use of HT (Fig. 2). This result is similar to that of a study conducted by Powell et al. (2014), in which late blight caused by *Phytophthora infestans* (Mont.) de Bary was significantly reduced in HT.

Although the production system significantly impacted yield attributes, the fruit quality of both crop species, for the most part, were unaffected (Tables 5 and 6). Lee et al. (2018) reported differences in volatile compound profiles of tomatoes grown in HT and OF in the same location as those of the present study. However, our results showed similar nutrient compound profiles and other chemical characteristics for pepper and tomato fruits grown in HT and OF, and both production systems yielded commercial quality fruits comparable to the national nutrient references (Tables 5 and 6). However, it is noteworthy that β-carotene in peppers and total ascorbic acid in tomatoes were 2-fold higher than the national reference standards in both HT and OF production systems. Considering that these two compounds are major determinants of the nutritional value of peppers and tomatoes, the production of high-quality vegetables in the Texas High Plains holds significant promise. However, further studies are needed to determine if the enhancement of those nutrients is region-specific or related to the cultivar or some other factor.

In relation to the impact of extreme weather events on crop water use, protection from high winds by the HT is the most advantageous factor in a climate like that of the Texas High Plains. This conclusion is supported by a previous study (Wallace et al., 2012) that verified that the HT reduced wind speed by 98%. Several studies that compared HT vs. OF production systems in various regions of the country identified changes in the microclimate of the HT environment, including increased air and soil temperatures, increased RH, and decreased incoming solar irradiance, as key benefits (O'Connell et al., 2012; Ogden and van Iersel, 2009; Wallace et al., 2012; Wien, 2009; Zhao and Carey, 2009). However, the impacts of reduced wind speed on the microclimate and water status of the soil and plants are still not well understood. Zhao and Carey (2009) reported that decreases in ET_0 by the HT were mostly due to reduced wind speeds and incoming solar irradiance, but they did not estimate the actual water use by ET_c. In this regard, the present study provided opportunities to compare water use and irrigation management in HT and OF production systems.

The WUE indicates the productivity and water use of a production system. Productivity is determined by the amount of incoming solar irradiance received in a production system. Therefore, the reduction in incoming solar irradiance in the HT observed in this study could imply a reduction in WUE (Tables 1 and 2). However, the reduction in incoming solar irradiance in the HT production system did not lower the productivity of peppers or tomatoes. Instead, peppers and tomatoes produced similar or more fruit FW in the HT. This was possibly due to the altered characteristics of the light caused by the material covering the HT. Because the clear woven covering has sunlight transmittance of ≈85%, the amount of direct sunlight available in the HTs was decreased (Tables 1 and 2). However, as direct sunlight passed through the cover, the light was dimmed and also diffused, and scattered light was more available to the leaves on the lower canopy (Ma et al., 2014). Although the top canopy receives less light, light absorbance by the plant as a whole increases through diffused light, thereby leading to increased biomass accumulation and crop yields (Li et al., 2014), which lead to increased WUE (Fig. 3).

This study demonstrated the benefits of modifications to the microenvironment with HT, compared with OF systems, in the Texas High Plains. The protection from inclement weather, which is common to the region in early spring, extended the growing season. The increased air temperatures in the HT ensured season extension and facilitated early crop establishment and subsequent increases in plant growth and yield. Even with less light intensity, crops produced higher yields for both peppers and tomatoes in the HT compared with the OF. The HT reduced the negative impact of hot, dry winds and decreased evapotranspirative water loss of the crops, resulting in greater WUE. Although the incidence of TSWV in both crop species was lower in the HT than in the OF production, the crop production system did not significantly impact overall fruit quality.

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