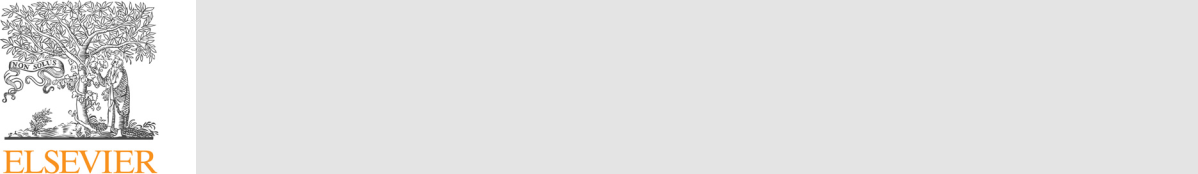
[Scientia Horticulturae 272 (2020) 109582](https://doi.org/10.1016/j.scienta.2020.109582)



Contents lists available at [ScienceDirect](http://www.sciencedirect.com/science/journal/03044238)



Scientia Horticulturae

journal homepage: [www.elsevier.com/locate/scihorti](https://www.elsevier.com/locate/scihorti)

Yield and fruit quality of high-tunnel tomato cultivars produced during the T oﬀ-season in South Texas 



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ARTICLE INFO

Keywords:

Solanum lycopersicum

Protected culture

Planting date

Growth habit

Oﬀ-season production

ABSTRACT

The Rio Grande Valley (RGV) of South Texas is one of the most diverse vegetable-producing regions in Texas. Traditionally, tomatoes in the RGV have been grown in open field during the spring and fall, but the production area has declined significantly due to the high pressure of pests and diseases. RGV open-field cultivation during winter is limited to cold-tolerant vegetables such spinach and cabbage due to the risk of cold days and nights. As an alternative, high tunnels oﬀer an environment protected against pests and diseases, wind, and low tem-peratures. Here, we studied the feasibility of RGV high-tunnel tomato production to identify the planting date, tomato type, and cultivars best suited for producing high-quality tomatoes during winter. The high tunnel maintained temperatures above 21 °C during chilly days without providing additional heat. In addition, whitefly and thrips populations remained low during most of the cropping season, although pesticide control was re-quired at crop establishment to lower their populations. Overall, higher yields were achieved in October com-pared to November planting and from determinate compared to indeterminate cultivars. Determinate tomato cultivars TAM Hot-Ty, Mykonos, and TAM HT1 transplanted in October produced up to 96.4, 129.13, and 85.98 t/ha, respectively. Among the cultivars tested, TAM Hot-Ty and TAM HT1 possessed the highest concentrations of soluble solids, with ° Brix > 5 %. In an organoleptic test, fruits from high tunnel tomatoes were ranked higher than Texas supermarket tomatoes imported from other regions in terms of flavor, color, and overall char-acteristics. This study demonstrates that tomato high-tunnel production oﬀers a viable alternative to open-field production in South Texas and could provide a source of high-quality locally produced tomatoes to Texas and nearby markets.

1. Introduction

Tomato (Solanum lycopersicum L.) is one of the most consumed ve-getables in the world ([Guan et al., 2018](#page8)). It is grown both for fresh use and for the processing industry, where it is used in products such as paste, whole peeled tomatoes, diced products, and various forms of juice, sauces, and soups ([Foolad, 2007](#page8)). Historically, Texas grew as many hectares of fresh tomatoes as Florida and California, the leading tomato-producing states in the US ([http://agcensus.mannlib.cornell.](http://agcensus.mannlib.cornell.edu/AgCensus/censusParts.do?year=1992) [edu/AgCensus/censusParts.do?year=1992](http://agcensus.mannlib.cornell.edu/AgCensus/censusParts.do?year=1992)). In 1959, for instance, Texas growers planted 9022 ha of tomatoes. Since then, however, a lack of adequate cultivars and the increased incidence of pest and disease



pressure, has caused Texas growers to migrate to other crops, largely abandoning fresh market tomatoes. As a result, Texas produced only

1. ha of harvested tomatoes in 2015 ([USDA-NASS, 2018](#page8)). To fill the concomitant demand gap, Texas imports tomatoes from Mexico and Canada ([Lopez, 2016](#page8)). However, “fresh” tomatoes grown in foreign countries must be picked green, trucked hundreds of miles, stored cold, and handled numerous times to arrive undamaged on Texas grocery shelves. Consumers are increasingly discontented with the flavor and quality of the product they are purchasing and are ready to pay more for better and higher-quality locally produced tomatoes ([Segovia-Coronel, 2014](#page8)).

Growing tomatoes in the subtropical climate of South Texas

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<https://doi.org/10.1016/j.scienta.2020.109582>

Received 13 November 2019; Received in revised form 7 June 2020; Accepted 26 June 2020

Available online 17 July 2020

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presents a challenge due to high temperatures and unpredictable weather patterns that severely limit the period when the temperatures are favorable for open field tomato production ([Masabni et al., 2016](#page8)). Because of its subtropical weather and geographical location, the Rio Grande Valley (RGV) in the southernmost part of Texas is also under high pressure from both endemic and new invasive pests and diseases. Economically important diseases in the region include tobacco mosaic virus (TMV), tomato spotted wilt virus (TSWV), Alternaria solani, and Fusarium oxysporum ([Aggie Horticulture, 2019](#page8)). Since 2002, however, the main disease aﬀecting tomato production in South Texas has been tomato yellow leaf curl virus (TYLCV), vectored by whiteflies. In to-mato plants infected with TYLCV, leaves curl upward along the edges and undergo strong crumpling and interveinal and marginal yellowing, negatively impacting tomato yield and quality.

Similar challenges are leading to the expansion of alternative pro-duction systems for vegetable production in other locations throughout the US. Among them, high tunnels, or hoop houses, are becoming in-creasingly popular, and tomatoes are the crop most commonly grown in high tunnels ([Knewtson et al., 2010](#page8); O'connell et al., 2012). High tun-nels are unheated, passively ventilated structures that can provide protection from adverse weather conditions, such as cold, precipitation, wind, and snow ([Healy et al., 2017](#page8); [Rogers and Wszelaki, 2012](#page8)). Fur-thermore, they allow uniform watering, reduce fruit-associated dis-orders, and the extension of the growing season ([Hunter et al., 2012](#page8); O'connell et al., 2012). By modulating the microenvironment in the high tunnels, growers can obtain greater yield than in the open field. [O’Connell et al. (2012)](#page8) reported a 33 % yield increase in tomatoes grown in high tunnels, along with lower incidence of tomato spotted wilt virus and gray leaf spot.

In addition to alternative production systems, appropriate selection of cultivars plays a fundamental role in crop production. In this regard, the use of cultivars with high-yield potential as well as pest and disease resistance is a high priority for growers, and it is essential to select cultivars adapted to the specific production system requirements to meet consumer demand. Tomato cultivars vary from determinate to indeterminate growth patterns ([Amaya et al., 1999](#page8); [Pnueli et al., 1998](#page8)). In tomato, growth habit determines plant architecture, influencing the relative growth of the vegetative and reproductive organs, speed of fruit set and maturation, fruit yield and quality, and ultimately grower production practices. Therefore, tomato growth habit is a crucial trait influencing decisions on what cultivars to select. Whereas determinate cultivars show controlled growth after initial fruit set, with synchro-nized flower and fruit production, the primary shoot of indeterminate cultivars keeps generating new branches, enabling further vegetative growth with continuous flower and fruit formation and providing continuous delivery of fresh tomatoes to the market ([Pnueli et al.,](#page8) [1998](#page8)). Determinate tomatoes also generally bear fruit earlier than in-determinate tomatoes.

In recent years, the tomato industry has increasingly emphasized the quality of tomato fruits, which is influenced by both genotype and production system ([Asensio et al., 2019](#page8); [Cebolla-Cornejo et al., 2011](#page8)). Tomato, shape, color, absence of damage, taste, aroma, and texture, among other traits, determine consumer preference ([Azodanlou et al.,](#page8) [2003](#page8); [Baldwin et al., 2008](#page8); [Foolad, 2007](#page8)). Among these, flavor is re-garded as having the greatest impact. Flavor in tomato fruit is influ-enced by sugars, acids, and volatile compounds and their interactions ([Baldwin et al., 2008](#page8)). Tomato fruits higher in sugar concentration and lower in acid have the most consumer appeal ([Baldwin et al., 2008](#page8); [Cebolla-Cornejo et al., 2011](#page8)).

The RGV is one of the most productive vegetable-growing areas of Texas ([Masabni et al., 2016](#page8)). However, alternative production systems to open-field production will be required to reactivate the nearly de-funct tomato industry. The area’s mild winters oﬀer the opportunity to grow tomatoes in high tunnels at a season when pest and disease pressure are lower and to reach oﬀ-season market windows. However, it is imperative to test the use of high tunnels under the specific

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agroecological conditions of the RGV before committing resources to this strategy, as climate and production requirements vary from place to place. In this study, we assessed the agronomic feasibility of tomato production during the winter season in high tunnels in the RGV in southern Texas to evaluate overall feasibility of the approach, to assess the eﬀect of planting date on yield and production quality, and to evaluate determinate and indeterminate cultivars for their adaptation to local production requirements. Our results indicate that in the RGV, early planting and determinate tomato cultivars resulted in higher yields and better quality than late planting and indeterminate cultivars, respectively.

2. Materials and methods

2.1. Site description and high tunnel design

The experiment was conducted in a high tunnel at the Texas A&M AgriLife Research and Extension Center at Weslaco, TX (26.1595 °N, 97.9908 °W). Soils of the research station are characterized as deep, moderately drained, clayey type according to the soil map of Hidalgo county (U.S. Department of Agriculture, 1981). The field soil pH of the experimental station is 8.2. The high tunnel site used in the present study resembles with the field station soil properties. Before our current study, rotation of vegetable and row crops were done. All the prior agricultural production operation in the current high tunnel site were performed under the guidelines of Texas A&M AgriLife Research sta-tion. The high-tunnel structure consisted of a 185 m2 hoop house with a single polythene film roof (6 mil poly cover) and a drop-down curtain (6 mil poly cover) sidewall system to passively control temperature. The sides of the structure were also covered with 50-mesh screen to reduce insect pressure.

2.2. Experimental design and Plant material

The experiment was arranged in split plot design with planting date as main plot and cultivars as subplot with three replications. The main plot consisted of two planting dates, October and November, in the winter growing seasons of 2016–2017 (season 1) and 2017–2018 (season 2). Six tomato cultivars, three with determinate growth habit (TAM Hot-Ty, TAM HT1, and Mykonos) and another three with in-determinate growth type (Torero, Floyd, and Prunus), were included. Among the cultivars, TAM Hot-Ty and TAM HT1 were developed by the Texas A&M University breeding program, whereas cultivars Mykonos (Seminis, St. Louis, MO), Torero and Prunus (DeRuiter, St. Louis, MO), and Floyd (Enza Zaden, Salinas, CA) were developed by private seed companies.

TAM Hot-Ty is small plant type, medium sized deep red globose fruit bearing F1 hybrid cultivar. It is heat tolerant and also resistance to Tomato yellow leaf curl virus and Fusarium wilt. TAM HT1 is large fruit bearing heirloom tomato and also tolerant to heat. Mykonos is a pop-ular F1 hybrid cultivar which grows medium to large plant and bear large deep oblate fruit. Mykonos is also resistant to gray leaf spot, Fusarium wilt and tomato mosaic and tomato yellow leaf curl virus. Cultivar Torero is a red beefsteak fruit bearing type and Prunus is roma-type tomato which produces plum shaped fruits. Cultivar Floyd is F1 hybrid which produces open, vigorous plants and produces oblate, beefsteak type shiny red color fruits.

2.3. Transplant production and transplanting to high tunnel

Seedlings were grown in greenhouse at Texas A&M AgriLife Research, Weslaco, TX. Greenhouse temperature were mantained at 24 ± 3oC with natural daylength hours. Seeds were sown in 72 – cell containing (each cell dimension =4 cm diameter X 5 cm height) plastic flats filled with BM 2 (Berger peat moss Ltd., Saint-Modeste, Quebec, Canada) as growing media. Seedlings were thinned to one per cell after

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germination. Five weeks old seedlings raised in greenhouse were transplanted into the high tunnel on October 10th and November 10th of each season. Seedlings were acclimated for two days outside the greenhouse before transplanting to the high tunnel. In high tunnel, plots were arranged in rows which were prepared by raising the bed. The bed rows were 1.542 m apart and were covered with 1.8 m wide and 0.032 mm thick white non-degradable plastic mulch. Plots within a row were placed at a distance of 1.2 m. Plots consisted of four plants from a cultivar, and cultivars were replicated thrice. In the 2016–2017 season, a distance of 0.61-m was maintained between plants for all determinate and indeterminate plants, while during 2017–2018, in-determinate cultivars were planted at a distance of 0.46 m between plants.

2.4. Systems management

Irrigation in high tunnel was managed through the subsurface drip irrigation system dug at 15 cm. The emitters in the drip tube were spaced every 30.5 cm and at a flow rate of 19 L per hour per 30.5 m. Watermark® sensors (Irrometer Company, Riverside, CA) were placed at 15–30 cm depth and irrigation was applied when the sensor reading reached 20 cBars. Plants were fertilized through the irrigation following recommended rates for South Texas ([Dainello and Anciso, 2004](#page8)). So-ludrip Tomatoes Stage fertilizer (Vital Fertilizers, Mission, TX) was used according to the manufacturer’s guide.

In high tunnel, tomato plants were supported through the trellis. In a plot, 1.52 m long three wooden stakes were placed in equal distance and the four horizontal layers of strings were passed through each of the stakes for determinate cultivars, while tomato vines were trained to the hanging tomato twine with a 3.5 cm diameter round plastic clips. Indeterminate plants were pruned regularly to maintain a single main stem ([Fridman et al., 2002](#page8)). During plant flowering, plants were gently shaken daily by to improve pollination.

A weather station was installed within the high-tunnel to monitor temperature and relative humidity (RH). To conserve heat during the chilly nights of December, January, and February, high-tunnel side-walls were rolled down when the minimum predicted outside tem-perature went below 10 °C. Weather conditions like temperature, hu-midity, rainfall, solar radiation outside the high-tunnel were received from weather station installed at Texas A&M AgriLife Research and Extension Center, Weslaco, TX.

2.5. Insect pest monitoring

Throughout the crop cycle, insect pest populations in the high tunnels were investigated using Pherocon AM no-bait yellow sticky traps (Trece Incorporated, Adair, OK). Six traps were set randomly in the high tunnel between planting dates. Sticky traps were collected weekly and stored in a 4 °C refrigerator until the insects were counted under a dissecting microscope.

2.6. Fruit quality traits

Sugar content, as total soluble solids (% Brix), and percentage of acidity were measured using a tomato PAL-BX|ACID3 Brix-Acidity Meter (ATAGO Inc., Bellevue, WA) following the manufacturer’s in-structions. Briefly, a representative longitudinal tomato section was cut, crushed, and sieved with a kitchen garlic crusher inside a piece of or-ganza fabric. Brix was measured on the device using an undiluted drop of tomato juice, while acidity was measured after diluting the juice in a 1/50 ratio with double-deionized water. Fruit firmness was measured as the maximum compression peak on a Force One™ penetrometer with a 3-mm tip (Wagner Instruments, Greenwich, CT).

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2.7. Sensory preference

A sensory test performed during season 1 evaluated consumers’ preferences for fresh tomato. Participants had the option to rate five tomato cultivars based on their color, flavor, and overall quality. During the sensory test, each participant tasted and compared samples of diced tomatoes from all five tomato cultivars grown during season 1 without knowing their identity. The tasting order of the tomato culti-vars was randomly assigned to avoid potential biases. Consumer pre-ference testing was performed with an untrained sensory panel com-prising 48 people who voluntarily participated in the evaluation. Participants were asked to rate fruits for flavor, color, and overall preferences on a structured scale from 1 (least favorite) to 5 (most fa-vorite). Similar sensory evaluation procedures have been implemented to assess consumers’ preferences for fresh tomatoes ([Asensio et al.,](#page8) [2019](#page8); [Azodanlou et al., 2003](#page8)).

2.8. Statistical analysis

Yield and fruit quality data were analyzed through analysis of var-iance using PROC MIXED (SAS Institute, 2016). Treatment eﬀects were separated by planting date, growth type, and cultivar within each season. Treatments were compared using Tukey’s honest significant diﬀerence multiple comparison at 0.05 level of significance. For the estimation of variance component and broad sense heritability (H2),

data from both seasons were combined. H2 for each trait was calculated using the equation H2 = *σg*2/ (*σg*2 + *σgy*2 + *σe*2), where *σg*2 , *σgy*2, and *σe*2 are the genotype, genotype by environment and residual variances, re-

spectively. *σg*2 , *σgy*2 , *σe*2 were derived by (MSg-MSgy)/ryp, (MSgy-MSe)/r and MSe, respectively. MSg, MSgy and MSe represent the genotype mean square, mean square of genotype by year, and residual mean square, respectively. In the present study, planting date was nested in year. Similarly, r, y, and p represent the number of replications, year and planting date, respectively.

3. Results and discussion

3.1. High-tunnel structures conserve heat on cold days and allow ventilation on warm days to maintain temperatures favorable for oﬀ-season tomato production

The RGV of South Texas is one of the few regions in the US suitable for growing vegetables during the winter months. When many states are facing freezing temperatures and/or snow, the RGV still enjoys many mild and even warm days. However, production in the open field is limited to cold-tolerant vegetables such as spinach and cabbage because of the risk of cold days and nights with temperatures near the freezing point that can aﬀect less tolerant crops such as tomato. For example, during our 2-year experiment, temperatures close to 0 °C occurred in the first week of January 2017, and at least a couple of recorded readings in December 2016 reached as low as 5 °C in open-field con-ditions (Supplemental Fig. S1). These temperatures would have sub-jected tomato plants in the open field to chilling injury ([Kinet and Peet,](#page8) [1997](#page8)).

In addition to the risk of low temperature extremes, the un-predictable climate of the RGV produces year-to-year temperature variation that severely limits the production of cold-sensitive crops, making open-field production of tomatoes highly risky. For example, during the two winter seasons evaluated in this study, the average overall seasonal (October to April) temperature diﬀered by ∼3.3 °C between the 2016–2017 and 2017–2018 seasons ([Table 1](#page8)), with Jan-uary 2018 averaging up to 5 °C colder than January 2017. In contrast to what was observed in the open field, average temperatures in the high tunnels were much more similar, at 24.6 °C and 24.3 °C in seasons 1 and 2, respectively ([Table 1](#page8)). These data indicate that despite the seasonal open-field temperature diﬀerences experienced in the RGV, high

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Table 1

Eﬀect of using a high tunnel on average monthly air temperature (°C) and relative humidity (%).

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Month |  |  |  | Season 1 (2016–2017) | | |  |  | Season 2 (2017–2018) | | | | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  |  | Temperature | |  |  | Relative humidity |  |  | Temperature |  |  | Relative humidity | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |
|  | Inside |  | Outside | Inside | | Outside |  | Inside | Outside |  | Inside | Outside | |
|  |  |  | |  | |  |  |  |  |  |  |  | |
| October | 31.1 | 26.5 | | 59.8 | | 68.4 |  | – | – |  | – | – | |
| November | 26.3 | 22.1 | | 71.0 | | 75.1 | 23.1 | | 22.4 | 61.2 | | 77.0 |  |
| December | 21.0 | 18.1 | | 81.1 | | 77.5 | 28.6 | | 15.4 | 56.0 | | 82.0 |  |
| January | 21.3 | 18.6 | | 78.7 | | 70.0 | 24.3 | | 13.6 | 41.6 | | 73.5 |  |
| February | 24.8 | 23.7 | | 75.4 | | 74.0 | 24.0 | | 20.6 | 72.6 | | 84.8 |  |
| March | 23.5 | 24.2 | | 81.1 | | 75.2 | 23.4 | | 23.4 | 71.0 | | 71.0 |  |
| April | – |  | – |  | – | – | 22.4 | | 23.2 | 80.7 | | 75.3 |  |
| Season | 24.6 | 22.2 | | 74.5 | | 73.4 | 24.3 | | 19.8 | 63.9 | | 77.3 |  |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |

tunnels consistently conserve heat and maintain favorable temperatures for tomato growth.

Compared to outside temperature, the high tunnel increased tem-perature by an average of 2.4 °C in season 1 and 4.5 °C in season 2 ([Table 1](#page8)). Nonetheless, during the colder months, temperatures were higher inside the high tunnel during season 2 than season 1 because during season 2, we rolled down the sidewall curtains to conserve heat, illustrating the benefits of high tunnels for passive temperature control. In the same way, several other studies have also reported moderate increases in temperature inside the high tunnel compared to the open field ([Jett et al., 2004](#page8); O'connell et al., 2012). Thus, during the coldest days, temperature diﬀerences of just a few degrees can provide pro-tection from cold injury and frost while also positively contributing to crop growth and development.

Moreover, although the high-tunnel side walls conserved heat during suboptimal cold periods, during warm days, especially at the beginning and the end of the seasons, they could be kept rolled up to allow passive ventilation when outside temperatures were high and it was necessary to remove excess heat, which can also be detrimental to crop productivity ([Table 1](#page8), Supplemental Fig. S1).

Finally, in contrast to the temperature, the relative humidity (RH) was similar inside and outside the high tunnels, at around 74 %, during season 1 ([Table 1](#page8)), indicating that enough ventilation was achieved in the high tunnel. However, during season 2, contrary to what was ex-pected, the RH was 13.4 % lower inside the high tunnels than in the open field ([Table 1](#page8)). This diﬀerence occurred from November to Feb-ruary, whereas the RH was similar inside and outside the high tunnel during March and April. These diﬀerences in RH can be attributed to rain in the first months of season 2 (Supplemental table S1), during which the high tunnel kept the ambient RH inside the structure drier.

Besides unpredictability of temperature in RGV, there was also an-nual variation in other climate parameters like rainfall and solar ra-diation. The experiment location received more rainfall during period from December to February in season 2 in 2017–2018 compared to the same time period in season 1, whereas, the case was just opposite during period from March to May (Supplemental Table S1). In account of solar radiation, there was great diurnal variation in both seasons (Supplemental Fig. 2). RGV received relatively increasing radiation since February onwards in season 1 and March onwards during season 2 studies (Supplemental Table S1). Such radiation would result the higher photosynthetic active radiation (PAR, 400–700 nm) than the optimum range of 400–500 μmol/m2/S for tomato plant growth ([Jones, 2007](#page8)) and lower the net photosynthetic rate ([Masabni et al., 2016](#page8)). This also emphasize the tomato production in protected environment in RGV.

3.2. Pest incidence inside the high tunnel coincided with the beginning and end of the production season

High tunnels serve as physical barriers that can limit the migration of insects from outside ([Majumdar et al., 2015](#page8); [Rogers et al., 2016](#page8)). In

addition, production during the winter months can help reduce pest pressure as low temperatures, resulting in seasonal declines of their populations. Therefore, we monitored insect populations weekly using yellow sticky traps to measure pest insect incidence during the crop cycle. While several insect pests can pose a threat to tomato production, pest surveys were focused on monitoring the incidence of whiteflies (Bemisia tabaci) and western flower thrips (Frankliniella occidentalis) because they are the vectors for tomato yellow leaf curl virus (TYLCV) ([De Barro et al., 2011](#page8); [Pakkianathan et al., 2015](#page8)) and tomato spotted wilt virus (TSWV), respectively ([Szostek et al., 2017](#page8); [Zitter et al., 1989](#page8)), the most important yield-limiting diseases of tomato in Texas.

As expected, the highest pest pressure inside the high tunnel cor-responded with the end of fall and beginning of spring, when outside insect populations are high, and pest pressure remained very low during the winter months ([Fig. 1](#page8)). Therefore, other pest control measurements, such as insecticide applications, need to be performed primarily during crop establishment, when plants are most susceptible. Unfortunately, in addition to crop pests, high tunnels may also exclude beneficial insects. [Majumdar et al. (2015)](#page8) reported that 50 % mesh shade cloths used in high tunnels result in reduced populations of ladybeetles and lacewings. On the other hand, the physical barrier created by high tunnels opens the possibility for integrating biological control agents by introducing commercially available beneficial insects.

Finally, although several studies have reported positive eﬀects of high tunnels on insect pest control ([Majumdar et al., 2015](#page8); [Rogers et al.,](#page8) [2016](#page8)), it has also been reported that some pests may be favored by the microclimate conditions inside the tunnel ([Ingwell et al., 2017](#page8); [Leach](#page8) [and Isaacs, 2018](#page8)). For example, oviposition of vine weevils (Otior-hynchus sulcatus) is favored in protected raspberry production systems ([Johnson et al., 2010](#page8)). Similarly, populations of pest insects, including spotted wing Drosophila, leafhoppers, and thrips, are reported to bear up to 6.6 times higher in high-tunnel-grown compared to open-field-grown raspberries ([Leach and Isaacs, 2018](#page8)). Furthermore, the utiliza-tion of insect mesh barriers reduces ventilation and can therefore result in higher incidence of certain diseases ([Majumdar et al., 2015](#page8)). For example, powdery mildew (Sphaerotheca macularis f. sp. fragariae) se-verity is reported to be higher on strawberries produced in tunnels (Xiao et al., 2001); however, in the same study, Botrytis fruit rot (Bo-trytis cinerea) was dramatically reduced. The authors suggest that mi-croclimatic conditions in the tunnel, such as short periods of leaf wet-ness and higher temperatures, contributed to reducing the incidence of Botrytis fruit rot while being more favorable to powdery mildew. These studies highlight the importance of careful planning for production in high tunnels so as to develop crop- and site-specific integrated pest management strategies to create economically and environmentally sustainable production systems.

3.3. Variation in traits among tomato cultivars

We observed the significant variation in yield, soluble solid content,

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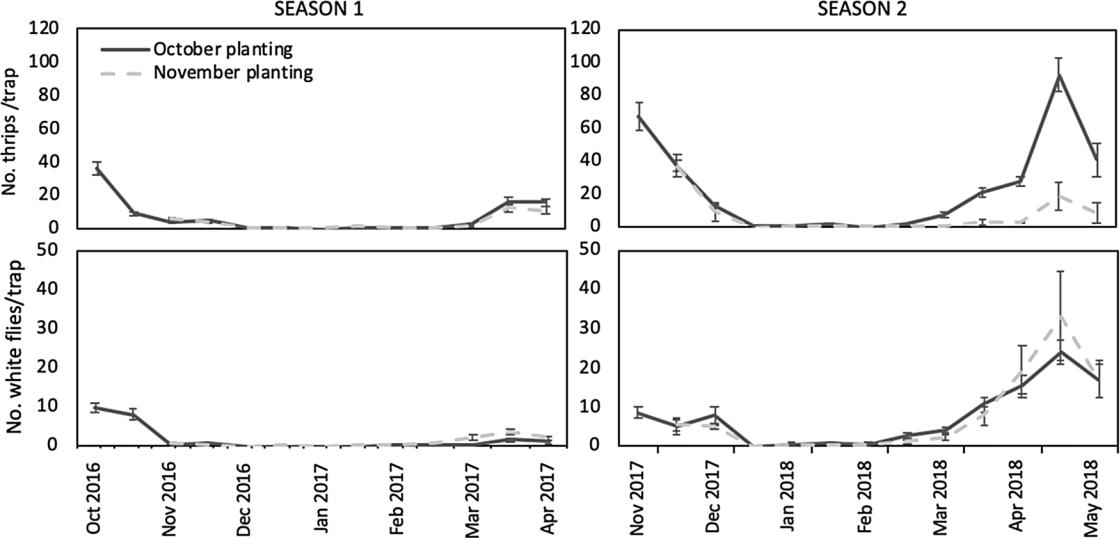


Fig. 1. Pest incidence during oﬀ-season high-tunnel tomato production in South Texas.

Table 2

Variance component and broad sense heritability (H2) for the four tomato fruit traits studied in high tunnel in South Texas during winter seasons 1 (2016 – 2017) and 2 (2017 – 2018).

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Trait |  |  | Eﬀects |  |  |  | Variance component |  | Broad sense heritability (H2) |
|  |  |  |  |  |  |  |  |  |  |
|  | Genotype (G) | | Year (Y) | Genotype\*Year (G\*Y) | G | | Y | G\*Y |  |
|  |  | |  |  |  | |  |  |  |
| Yield | \*\* | | \* | ns | 197.983 | | 94.566 | 98.333 | 0.276 |
| Soluble solid content | \*\* | | \*\* | ns | 0.302 | | 0.0492 | 0.013 | 0.75 |
| Titrable acidity |  | ns | \*\* | ns | 0.006 | | 0.0731 | 0.001 | 0.058 |
| Firmness | \*\* | | \*\* | \*\* | 0.004 | | 0.0259 | 0.005 | 0.233 |

Note: \* = P < 0.05, \*\* = P < 0.01, ns = nonsignificant.

Table 3

Eﬀects of planting date, growth habit, and cultivar on marketable yield of high-tunnel tomatoes. Values are means ± Std. Error; those with diﬀerent letters are statistically significant at Tukey’s honest significant diﬀerence multiple comparison at P < 0.05, N = 3.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Planting | Growth habit | Cultivar |  | Season 1 (t/ha)[\*](#page8) | |  |  |  |  | Season 2 (t/ha) |  |  |
|  |  |  |  |  | |  | |  |  |  |  |  |
|  |  |  | By planting date | By growth habit | | By cultivar | | | By planting date | By growth habit | By cultivar |  |
|  |  |  |  |  |  |  | | |  |  |  |  |
| Oct | Determinate | TAM Hot-Ty | 79.43 ± 9.61 a | 112.76 | ± 13.41 a | 96.4 ± 14.57 ab | | | 65.52 ± 7.73 a | 82.03 ± 9.01 a | 77.91 ± 22.77 a |  |
|  |  | Mykonos |  |  |  | 129.13 | ± 20.48 a | |  |  | 82.19 ± 5.24 a |  |
|  |  | TAM HT1 |  |  |  |  | – | |  |  | 85.98 ± 20.33 a |  |
|  | Indeterminate | Floyd |  | 57.22 | ± 6.36 b | 67.21 | ± 6.86 b | |  | 40.76 ± 4.44 b | – |  |
|  |  | Torero |  |  |  | 66.29 ± 12.79 b | | |  |  | 48.63 ± 1.76 ab |  |
|  |  | Prunus |  |  |  | 38.16 | ± 1.79 c | |  |  | 32.89 ± 5.79 b |  |
| Nov | Determinate | TAM Hot-Ty | 55.89 ± 2.96 b | 56.52 | ± 2.96 a | 59.98 | ± 4.46 a | | 55.18 ± 6.07 a | 66.25 ± 7.04 a | 67.67 ± 14.24 ab |  |
|  |  | Mykonos |  |  |  | 53.06 | ± 3.49 a | |  |  | 60.02 ± 15.94 ab |  |
|  |  | TAM HT1 |  |  |  |  | – | |  |  | 71.07 ± 10.28 a |  |
|  | Indeterminate | Floyd |  | 55.48 | ± 4.66 a | 52.44 | ± 8.32 a | |  | 38.57 ± 6.89 b | – |  |
|  |  | Torero |  |  |  | 65.98 | ± 8.71 a | |  |  | 45.64 ± 2.74 b |  |
|  |  | Prunus |  |  |  | 48.02 | ± 5.31 a | |  |  | 31.50 ± 13.42 b |  |

\* Extrapolated values from experimental plots.

and fruit firmness among the cultivars ([Tables 2–6](#page8)). Year eﬀect was significant for all the traits and the interaction of cultivar by year was significant for the fruit firmness ([Table 2](#page8)). Similarly, traits displayed the variation for broad sense heritability (H2). The higher H2 value (0.75) for the soluble solid content suggest the higher degree of genetic control for this trait. Lower H2 value for the yield, titrable acidity and fruit firmness suggest these traits sensitive to the environmental condition ([Bauchet et al., 2017](#page8)), and emphasize the importance of production environment.

3.4. Early high-tunnel planting and determinate tomato varieties maximize oﬀ-season yields in South Texas

Traditionally, tomatoes are produced in the RGV during the spring and fall in the open field ([Elsayed-Farag et al., 2018](#page8)). Spring planting starts in late February or early March for harvest in May and June, whereas fall planting starts in late August or early September for a harvest in December before temperatures drop low enough to cause crop chilling injury. However, we found no previous studies of the appropriate planting time for oﬀ-season tomato production in the RGV. During our two test seasons, we evaluated planting dates by trans-planting seedlings into the high tunnels in mid-October and mid-

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Table 4

Eﬀects of planting date, growth habit, and cultivar on fruit total soluble solids in high-tunnel tomatoes in South Texas. Values are means ± Std. Error; those with diﬀerent letters are statistically significant at Tukey’s honest significant diﬀerence multiple comparison at P < 0.05, N = 3.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Planting | Growth habit | Cultivar |  |  | Season 1 Brix (%) |  |  |  | Season 2 Brix (%) |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | By planting date | | By growth habit | By cultivar |  | By planting date | By growth habit | By cultivar | |
|  |  |  |  |  |  |  |  |  |  |  | |
| Oct | Determinate | TAM Hot-Ty |  | 4.10 ± 0.11 a | 4.47 ± 0.14 a | 4.72 ± 0.11 a |  | 4.45 ± 0.13 a | 4.8 ± 0.08 a | 4.89 ± 0.10 a | |
|  |  | Mykonos |  |  |  | 4.21 ± 0.14 ab |  |  |  | 4.52 ± 0.06 b | |
|  |  | TAM HT1 |  |  |  | – |  |  |  | 5.03 ± 0.06 a | |
|  | Indeterminate | Floyd |  |  | 3.86 ± 0.10 b | 3.60 ± 0.04 c |  |  | 3.90 ± 0.11 b | – | |
|  |  | Torero |  |  |  | 3.78 ± 0.09 bc |  |  |  | 3.66 ± 0.07 d | |
|  |  | Prunus |  |  |  | 4.2 ± 0.15 ab |  |  |  | 4.14 ± 0.04 c | |
| Nov | Determinate | TAM Hot-Ty |  | 3.67 ± 0.17 b | 4.20 ± 0.22 a | 4.56 ± 0.19 a |  | 4.57 ± 0.15 a | 4.90 ± 0.16 a | 5.24 ± 0.09 a | |
|  |  | Mykonos |  |  |  | 3.84 ± 0.27 ab |  |  |  | 4.36 ± 0.25 bc | |
|  |  | TAM HT1 |  |  |  | – |  |  |  | 5.10 ± 0.18 ab | |
|  | Indeterminate | Floyd |  |  | 3.31 ± 0.16 b | 3.01 ± 0.25 b |  |  | 4.08 ± 0.17 b | – | |
|  |  | Torero |  |  |  | 3.28 ± 0.24 b |  |  |  | 3.75 ± 0.03 c | |
|  |  | Prunus |  |  |  | 3.66 ± 0.33 ab |  |  |  | 4.40 ± 0.19 bc | |
|  |  |  |  |  |  |  |  |  |  |  |  |

Table 5

Eﬀects of planting date, growth habit, and cultivar on fruit total acidity in high-tunnel tomatoes in South Texas. Values are means ± Std. Error; those with diﬀerent letters are statistically significant at Tukey’s honest significant diﬀerence multiple comparison at P < 0.05, N = 3.

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Planting | Growth habit | Cultivar | Season 1 acidity (%) |  |  |  |  | Season 2 acidity (%) |  |  |  |  |
|  |  |  |  |  |  | |  |  |  |  | |  |
|  |  |  | By planting date | By growth habit | By cultivar | | | By planting date | By growth habit | By cultivar | | |
|  |  |  |  |  |  | | |  |  |  | | |
| Oct | Determinate | TAM Hot-Ty | 0.65 ± 0.04 b | 0.77 ± 0.06 a | 0.71 ± 0.04 ab | | | 0.65 ± 0.04 b | 0.58 ± 0.03 a | 0.508 ± 0.05 ab | | |
|  |  | Mykonos |  |  | 0.82 | ± 0.12 a | |  |  | 0.66 | ± 0.04 a | |
|  |  | TAM HT1 |  |  | – |  |  |  |  | 0.58 | ± 0.04 a | |
|  | Indeterminate | Floyd |  | 0.56 ± 0.04 b | 0.68 ± 0.08 ab | | |  | 0.46 ± 0.03 b | – |  |  |
|  |  | Torero |  |  | 0.48 | ± 0.01 b | |  |  | 0.41 | ± 0.02 b | |
|  |  | Prunus |  |  | 0.52 | ± 0.05 ab | |  |  | 0.52 | ± 0.03 ab | |
| Nov | Determinate | TAM Hot-Ty | 1.2 ± 0.14 a | 1.54 ± 0.28 a | 1.45 ± 0.62 a | | | 0.58 ± 0.06 a | 0.55 ± 0.02 a | 0.57 ± 0.04 a | | |
|  |  | Mykonos |  |  | 1.64 | ± 0.12 a | |  |  | 0.50 | ± 0.03 a | |
|  |  | TAM HT1 |  |  | – |  |  |  |  | 0.58 | ± 0.01 a | |
|  | Indeterminate | Floyd |  | 0.98 ± 0.09 a | 0.99 ± 0.11 a | | |  | 0.63 ± 0.17 a | – |  |  |
|  |  | Torero |  |  | 1.06 | ± 0.05 a | |  |  | 0.43 | ± 0.01 a | |
|  |  | Prunus |  |  | 0.89 | ± 0.29 a | |  |  | 0.83 | ± 0.32 a | |
|  |  |  |  |  |  |  |  |  |  |  |  |  |

Table 6

Fruit firmness is unaﬀected by planting date, growth habit, and cultivar in high-tunnel tomatoes in South Texas. Values are means ± Std. Error; those with diﬀerent letters are statistically significant at Tukey’s honest significant diﬀerence multiple comparison at P < 0.05, N = 3.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Planting | Growth habit | Cultivar |  | Season 1 fruit firmness (kgF) | | |  | Season 2 fruit firmness (kgF) | |  |  |
|  |  |  |  |  |  |  |  |  |  |  |  |
|  |  |  | By planting date | | By growth habit | By cultivar |  | By planting date | By growth habit | By cultivar | |
|  |  |  |  |  |  |  |  |  |  |  | |
| Oct | Determinate | TAM Hot-Ty |  | 0.54 ± 0.004 a | 0.54 ± 0.006 a | 0.53 ± 0.01 a |  | 0.89 ± 0.04 a | 0.82 ± 0.06 a | 0.73 ± 0.05 bc | |
|  |  | Mykonos |  |  |  | 0.55 ± 0.002 a |  |  |  | 0.68 ± 0.011 c | |
|  |  | TAM HT1 |  |  |  |  |  |  |  | 1.07 ± 0.06 a | |
|  | Indeterminate | Floyd |  |  | 0.54 ± 0.006 a | 0.54 ± 0.002 a |  |  | 1 ± 0.04 a |  |  |
|  |  | Torero |  |  |  | 0.53 ± 0.016 a |  |  |  | 0.96 ± 0.08 ab | |
|  |  | Prunus |  |  |  | 0.55 ± 0.006 a |  |  |  | 1.04 ± 0.04 a | |
| Nov | Determinate | TAM Hot-Ty |  | 0.53 ± 0.005 a | 0.54 ± 0.005 a | 0.54 ± 0.01 ab |  | 0.81 ± 0.04 a | 0.76 ± 0.04 a | 0.64 ± 0.07 a | |
|  |  | Mykonos |  |  |  | 0.55 ± 0.003 a |  |  |  | 0.78 ± 0.015 a | |
|  |  | TAM HT1 |  |  |  |  |  |  |  | 0.87 ± 0.03 a | |
|  | Indeterminate | Floyd |  |  | 0.53 ± 0.007 a | 0.54 ± 0.004 ab |  |  | 0.86 ± 0.07 a |  |  |
|  |  | Torero |  |  |  | 0.50 ± 0.007 b |  |  |  | 0.88 ± 0.15 a | |
|  |  | Prunus |  |  |  | 0.55 ± 0.012 a |  |  |  | 0.85 ± 0.04 a | |
|  |  |  |  |  |  |  |  |  |  |  |  |

November. The total marketable yield was higher after the earlier planting in both seasons. During season 1, the average yields from October planting were 79.43 t/ha, while those from November planting were 55.89 t/ha ([Table 3](#page8)), representing a statistically significant (P = 0.0053) 42 % diﬀerence in yield. Similarly, during season 2, October and November planting average yields were of 65.52 and 55.18 t/ha, respectively, representing a 19 % diﬀerence in yield, although this did not reach statistical significance ([Table 3](#page8)).

Plants transplanted in November were comparatively younger and may have been more vulnerable during their vegetative and re-productive stages to the relatively low temperatures during December

and January. On the other hand, plants that were planted in October received a comparatively longer exposure to favorable warm tempera-tures and longer photoperiod, which could have imparted better agro-nomic growth and, thus, greater yield ([Ayankojo et al., 2018](#page8); [Neild and](#page8) [Seeley, 1977](#page8)). These observations indicate how crucial the optimal transplanting date is for crop productivity, as has been described in several other reports ([Ahammad et al., 2009](#page8); [Elsayed-Farag et al., 2018](#page8); [Singh et al., 2015](#page8)).

We also evaluated the eﬀect of plant growth habit in high-tunnel production in the RGV. Whereas open-field production traditionally has focused on early determinate tomato cultivars ([Elsayed-Farag et al.,](#page8)

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[2018](#page8)), tomato production in high tunnels might provide the possibility of extending the harvesting period through the utilization of in-determinate-type tomato cultivars. However, our results indicated that under RGV conditions, determinate-type tomatoes produce higher yields than indeterminate tomatoes among the cultivars tested in this study (P = 0.0008 in season 1 and P = 0.0002 in season 2). With the exception of the season 1, November planting date, for which only marginally higher yields were observed for the determinate cultivars, all other comparisons showed statistically significant diﬀerences. For the season 1 October planting and the season 2 October and November plantings, yields were 97, 101, and 71 % higher on average in de-terminate compared to indeterminate cultivars ([Table 3](#page8)). The pruning operation required to establish a single main stem may have limited the yield of indeterminate cultivars in this study, as reported by others ([Peet and Welles, 2005](#page8); [Saltveit, 2005](#page8)).

Furthermore, when evaluating cultivar performance, we observed a significant main eﬀect of cultivar on marketable yield (P = 0.0053 in season 1 and P = 0.0107 in season 2). During season 1, cv. Mykonos (129.13 t/ha) produced the highest yields, followed by cv. TAM Hot-Ty (96.4 t/ha), whereas during the second year, the highest-yielding cul-tivar was cv. TAM-HT1 (85.98 t/ha), which had not been tested during season 1, followed by cv. Mykonos (82.19 t/ha) and cv. TAM HT1 (71.07 t/ha) ([Table 3](#page8)). However, the yield diﬀerences observed be-tween the diﬀerent determinate cultivars were not significant at α = 0.05, suggesting that any of these three cultivars could reasonably be chosen for production in the RGV under high-tunnel conditions. Moreover, choosing which cultivar to grow will depend on market demands and observed yields. For example, cv. Mykonos produces extra-large beefsteak tomatoes, whereas cv. TAM Hot-Ty produces large ones. On the other hand, TAM HT1 is a “heirloom”-type extra-large tomato, which could potentially be sold in specialty markets at a higher price.

The high-tunnel data were consistent with the results obtained in the open field in the RGV by [Elsayed-Farag et al. (2018)](#page8), in which cv. TAM Hot-Ty (51.65 t /ha) and Mykonos (50.78 t/ha) also performed better than cv. Torero (48.33 t/ha) and Prunus (35.72 t/ha). Although direct comparisons cannot be made between the results of their open-field study and this high-tunnel study, the data strongly suggest that marketable yields are higher in high-tunnel compared to open-field production in South Texas. Similarly, [O’Connell et al. (2012)](#page8) reported that tomato yield increased 33 % in high tunnels compared to open-field production.

3.5. Planting date eﬀects on solids and acidity varies season-to-season

In addition to their eﬀects on yield, we also evaluated the eﬀects of planting date and cultivar growth habit on fruit sweetness (total soluble solids content), total acidity, and firmness. During season 1, total so-luble solids concentration (Brix %) as a measurement of sweetness in tomato fruits diﬀered significantly by planting date (P < 0.0001). Generally, glucose and fructose are considered the major sugars in to-mato fruit, along with trace amounts of sucrose ([Baldwin et al., 2008](#page8); [Foolad, 2007](#page8)). In this study, we did not isolate diﬀerent sugars sepa-rately; therefore, the data presented here represent cumulative of glu-cose, fructose, and sucrose.

We observed significantly higher Brix in the October planting (4.10 %) compared to the November planting (3.67 %) in season 1, re-presenting a 12 % diﬀerence in total soluble solids ([Table 4](#page8)). However, a similar eﬀect was not observed in season 2. Furthermore, the sugar concentration in the fruits varied between cultivars in both seasons (P

* 0.0034 in season 1 and P < 0.0001 in season 2) and on the basis of plant growth habit (P < 0.0001 in season 1 and P < 0.0001 in season 2). Fruits of the determinate cultivars TAM Hot-Ty, Mykonos, and TAM HT1 had overall higher Brix values than those from indeterminate cultivars ([Table 4](#page8)). The average sugar contents in fruits from cv. TAM

Hot-Ty (4.56 ± 0.22 %–5.24 ± 0.09 %), Mykonos (3.84 ± 0.27

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%–4.52 ± 0.06 %), and Prunus (3.66 ± 0.33 %–4.40 ± 0.19 %) in this study were similar to those previously reported in open-field trials at the same location ([Anciso, 2016](#page8)). This suggests that under RGV oﬀ-season conditions, high-tunnel soluble solid content is not aﬀected, in contrast to a previous report in which low sugar was observed in pro-duce cultivated under protected conditions ([Cebolla-Cornejo et al.,](#page8) [2011](#page8)). Since that study was performed in Spain, the contradictory re-sults suggest that the specific environment and its interaction with the cultivars utilized has a substantial impact on observed soluble solid content. Finally, among the cultivars, determinate cultivars TAM Hot-Ty and TAM HT1 were the two with the highest sugar concentration, with Brix up to 5.24 % and 5.10 %, respectively ([Table 4](#page8)).

Meanwhile, tomato fruits harvested after October compared to November planting in season 1 showed lower acid levels (P = 0.0015). However, in season 2, no significant eﬀect of planting time was ob-served for this trait ([Table 5](#page8)). Like the sugar concentration, the eﬀect of cultivar growth habit on fruit acid content was not consistent across planting dates over the seasons ([Table 5](#page8)). October planting in both season 1 (P = 0.049) and season 2 (P = 0.019) resulted in statistical diﬀerences between determinate (0.77 % and 0.58 %, respectively) and indeterminate (0.56 % and 0.46 %, respectively) tomatoes. Citric acid is described as the major acid in tomato, followed by malic acid and glutamic acid, respectively ([Baldwin et al., 2008](#page8)). As for sugars, we did not isolate individual types of acids; therefore, the acidity data pre-sented in this study represent cumulative results for the above-men-tioned acids.

Finally, fruit firmness did not diﬀer between planting date or growth habit, and cultivar eﬀect on fruit firmness was inconsistent ([Table 6](#page8)). For example, in season 1, a single diﬀerence in firmness was observed between cultivars, as cv. Torero (P = 0.006) had significantly lower firmness content than the other cultivars; however, in season 2, no statistically significant diﬀerences were observed. Although no di-rect comparison was made between seasons, the data show higher firmness values in season 2 tomatoes compared to season 1, suggesting that diﬀerences in environmental conditions between the 2 years may have aﬀected fruit firmness. Finally, given that a firmness value of 0.14 kgF is considered the threshold for marketing purposes ([Batu, 2004](#page8)), we confirmed that all the tomatoes produced in this study met market standards in this regard, since all firmness values were > 0.14 kgF ([Table 6](#page8)).

3.6. Sensory analysis indicates consumer preference for tomatoes produced in high tunnels

Samples of diced tomatoes from season 1 were oﬀered to tasters to evaluate for color, flavor, and overall preference. Tomatoes purchased from the local grocery store were included as a control. Consumer preference testing was performed with an untrained sensory panel comprising 48 people who voluntarily participated in the evaluation. Among the participants, 32 % were aged 18–35 years, 34 % were 36–50 years old, and 34 % were > 51 years old. Among them, 40 % were females, 68 % Hispanic, and 23 % non-Hispanic white. Participants were asked to rate fruits for flavor, color, and overall preferences on a structured scale from 1 (least favorite) to 5 (most favorite). Based on this scale, we considered a rating of 1 or 2 a favorable consumer pre-ference.

Fruits of TAM Hot-Ty and Mykonos were the most preferred (that is, were given a color rating of 1 or 2), by 71 % and 62 % of the partici-pants, respectively, whereas the Floyd cultivar and the supermarket tomato control received the lowest preference ratings, with only 21 % and 26 % of the participants giving these favorable ratings, respectively ([Fig. 2](#page8)). In terms of flavor, tomatoes from cv. Torero and TAM Hot-Ty received the highest ratings, with 59 % and 54 % of participants rating them as preferable, respectively. As with color preference, cv. Floyd (30 %) and the supermarket control (21 %) had the lowest participant flavor preference. Overall, cv. Tam Hot-Ty had the highest rating when

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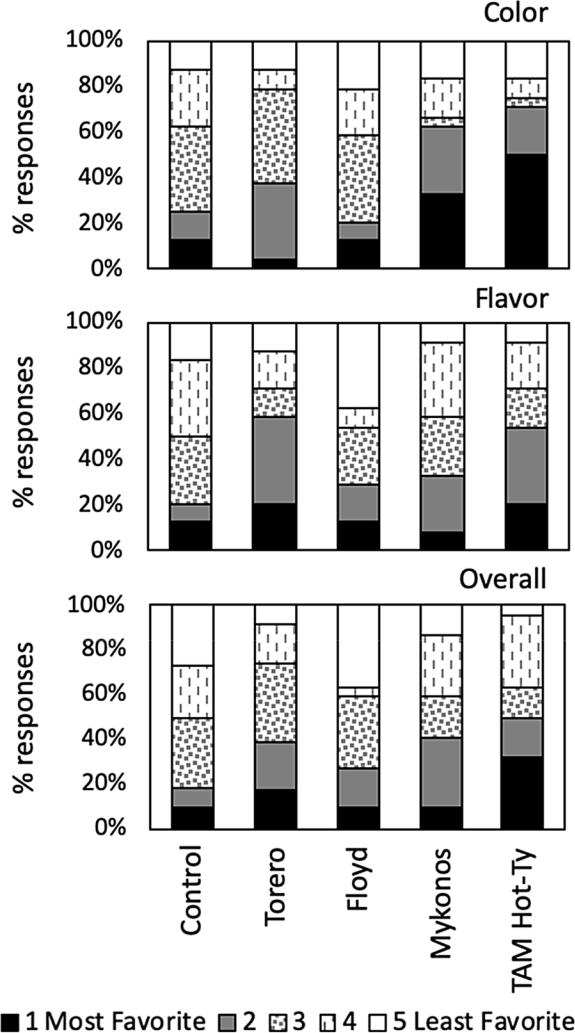


Fig. 2. Sensory evaluation of high-tunnel-produced tomatoes. Supermarket tomato was used as a control.

all characteristics were combined, with 50 % of participant preference ratings at 1 or 2. This consumer preference for tomatoes from cv. TAM Hot-Ty could be partially explained by its high lycopene content, which results in the intense red color of this cultivar ([Lee et al., 2019](#page8)), and by its high sugar concentration compared to the rest of the cultivars tested in season 1, when the savory test was performed, since it has been re-ported that higher sugar concentration correlates with favorable con-sumer preference ([Baldwin et al., 2008](#page8); [Foolad, 2007](#page8)).

The higher sensory evaluation rating of high-tunnel tomatoes over supermarket tomatoes in this study is consistent with the results re-ported for sensory evaluation of high-tunnel- and field-grown tomatoes by [Krizek et al. (2006)](#page8). Generally, tomatoes sold in supermarkets are harvested at the mature green, breaker stage, well before the table-ripe stage. Increases in sugar concentration ([Beckles, 2012](#page8); [Kader et al.,](#page8) [1977](#page8)) and decreases in acid concentration ([Gautier et al., 2008](#page8)) are reported to occur during the ripening process. As a climacteric type, tomato fruit ripen even oﬀ the plants if harvested at the proper maturity stage. However, there are several reports of diﬀerences in metabolite composition, resulting in lower sugar and higher acid content, in to-mato fruits ripened oﬀ the vine compared to on the vine ([Betancourt](#page8) [et al., 1977](#page8); [Kader et al., 1977](#page8)). This may partly explain the overall greater flavor of tomato fruits produced in high tunnels and harvested at the table-ripe stage compared to supermarket tomatoes, in addition to any eﬀects of cultivar and high-tunnel production ([Causse et al.,](#page8) [2010](#page8); [Figas et al., 2018](#page8)).

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3.7. High-tunnel production oﬀers a viable alternative to open-field production in South Texas

The unpredictability and variability of weather conditions in South Texas pose challenges for open-field tomato production the during winter season. This study indicates the usefulness of high-tunnel pro-duction system in mitigating such weather challenges and extending the tomato growing season beyond traditional spring and fall open-field production periods. The data from this high-tunnel study in South Texas indicate that better tomato yield and good market quality can be achieved through early planting in October as opposed to November. In addition, consistently greater yields and higher quality were obtained with determinate (i.e., TAM Hot-Ty, TAM HT1, and Mykonos) com-pared to indeterminate cultivars, implying that the former are better adapted to the high tunnel in this agroecological region. Early, local, and high-quality tomatoes produced during the oﬀ-season could pro-vide economic benefits by commanding premium prices on the nearby market ([Ward et al., 2011](#page8); [Knewtson et al., 2010](#page8)), as a viable alter-native for the Texas RGV tomato industry.

Author Contributions

DK performed analysis and drafted manuscript. DK and TM per-formed field maintenance and yield/quality data collection. IB per-formed insect monitoring. SZ, TM, and CA performed quality evalua-tions. CL, KC and CA designed experiments and supervised trials. All authors reviewed manuscript.

Declaration of Competing Interest

The authors declare that they have no competing interest.

Acknowledgements

We thank Samantha Serna, Alexandra Hernandez, and Alondra Menchaca at the Texas A&M AgriLife Research and Extension Center for assistance with field work, harvesting, and measuring of fruit quality traits. Research was funded by the Texas Department of Agriculture Specialty Crop Block grant SC-1718-024 assigned to C.A.A., K.C., and C.L. and Texas A&M AgriLife grant FY17-96180 and FY18-96180 as-signed to C.A.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.scienta.2020.109582>.

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