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A comparison of strawberry (*Fragaria x ananassa*) cultivars affected by different cultural practices in two production systems

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Strawberry cultivar performance affected by various cultural practices was investigated in two production systems. The first study investigated strawberry yield, fruit quality, and production timing of eight cultivars when using black and red plastic mulches in a high tunnel production system. The high tunnel increased air temperatures and advanced strawberry fruiting by four to six weeks compared to local open-field production. The second study investigated plant growth, yield, and fruit quality of 10 cultivars fertilized with organic or conventional fertilizer and irrigated once or twice daily with the same total irrigation volume in a container system. Strawberry cultivars varied in their yield and quality variables including soluble solids contents, firmness, and titratible acidity in the two production systems. Mulch color, fertilizer type, and irrigation frequency had varying effects on the growth microenvironment, fruit yield, and certain quality variables.

DEDICATION

I would like to dedicate this work to my wife Sarah. I would not have come this far without her love and support.

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I would like to thank my major professor, Dr. Tongyin Li, for all of her help and encouragement throughout this process. I would also like to thank my mother Margaret, my father Tom, and my big sister Kathy for always being there for me. I would also like to thank my 105 year old grandma Kay who has always been an inspiration to me.

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LITERATURE REVIEW

Introduction

The United States is the world's second largest producer of strawberries (*Fragaria ×ananassa* Duch.) (FAO, 2018). In 2017, U.S. produced 1.6 billion pounds of strawberries, with an industry value of near $3.5 billion, second only to apple (*Malus domestica* Borkh.) (AgMRC, 2019; Samtani, 2019). Most of the strawberries sold commercially are different cultivars of the hybrid plant *Fragaria × ananassa* Duch. This natural hybrid of *Fragaria virginiana* Duch. and *Fragaria chiloensis* L. has been adapted to many different growing conditions and its success has supplanted almost all other *Fragaria* species (Husaini and Neri, 2016). Strawberry is one of the most consumed fruits in the U.S., serving as an important component of a healthy diet (Giampieri et al. 2012). Per capita consumption of fresh strawberries increased from 2 lbs in 1980 to 7.2 lbs in 2018 (AgMRC, 2019; Shahbandeh, 2019; USDA, 2014). The leading states for strawberry production in the U.S. are California and Florida, producing approximately 91% and 8% of the nation's strawberry crop (USDA, 2019). Compared to large-scale production in California and Florida, strawberry production in midsouthern states occurs mainly on small- to medium-sized farms often diversified with other vegetable crops, accounting for 0.5% of total U.S. production (Samtani et al., 2019). Strawberries are valued not only for basic nutritional components including sugars, mineral nutrients, and vitamins, but they are also rich in bioactive compounds such as anthocyanins, quercetins, and catechins. These bioactive compounds are known to have antioxidant capacity, scavenge free radicals, and introduce health benefits such as slowing down aging, preventing cardiovascular diseases, inflammation, and certain types of cancers (Giampieri et al., 2014; Miao et al., 2017).

Strawberry Types

Cultivated strawberry plants are classified into three types of cultivars based on their flowering response to photoperiods: June-bearing, everbearing, or day-neutral (Hancock, 1999). June-bearing strawberries initiate flowering in response to a short photoperiod of 14 hours or less, or low temperatures below 15 °C, and typically produce one flush of fruit in spring. (Hancock, 1999; Husaini and Neri, 2016). June-bearing cultivars are also sometimes subdivided into early season, mid-season and late season with late season plants starting about two weeks later than early season plants. Ever-bearing cultivars initiate flower buds with days of greater than 12 h, resulting in a fall harvest or two crops in one year (Gu et al., 2017). Day-neutral strawberry plants can produce crowns and flower buds whenever the temperature is within a favorable range of 4 to 29°C regardless of the day length (Rowley et al., 2011). These distinctions are not necessarily completely rigid. Bradford et al. (2010) found that both June-bearing and day-neutral cultivars had temperature ranges where flowering occurred under long or short photoperiods. Cultivars developed as day neutral in a particular environment might behave as short day or June bearing in higher temperature climates. It has been suggested that each cultivar has a particular response curve for the interaction of temperature and photoperiod (Heide et al., 2013). Commercial production of strawberries uses mostly June-bearing cultivars or a combination of June-bearing and day-neutral cultivars, with ever-bearing cultivars rarely grown outside of home gardens. There has been increasing interest in using day-neutral cultivars to extend harvest season (Gu et al., 2017; Gude et al., 2018). Samtani et al. (2019) compared day-neutral and June-bearing cultivars grown under high tunnels at two different sites in North Carolina. Only one of the sites showed significant difference in yield between cultivar types. However, in both locations, the day-neutral cultivars began producing berries more than a month before the June-bearing cultivars. Research by Khanizadeh et al. (2008) suggests that June-bearing strawberries have greater phenolic content and antioxidant capacity than day-neutral strawberries although they also found large variation among different June-bearing cultivars.

Plasticulture in Strawberry Production

Commercial strawberry production in the U.S. mainly uses annual hill production (AHP) system with plasticulture (California Strawberry Commission, 2018; Poling, 2015). Polyethylene films are tightly laid onto raised planting beds leading to increased heat and moisture retention of the soil underneath, and thereby producing strawberry fruits with higher levels of phenolic compounds compared to fruits produced in a matted-row system in Canada (Fan et al., 2011). Plastic films are extensively used for controlling weeds and keeping fruit clean and out of direct contact with the soil. The soil under film can be up to 3 °C warmer than the surrounding soil (Lamont, 1993). The use of plastic films also has benefits such as earlier fruiting, reduced soil moisture loss, reduced fertilizer leaching (Lamont, 1993), increased yields and improved fruit quality, earlier maturity, and improved insect management (Lamont 2009).

Black, white and clear films are commonly used and investigations with different colors of plastic film have been conducted (Decoteau et al., 1989; Miao et al., 2017; Shiukhy et al., 2015). Research found much greater yields for strawberry plants grown under colored mulch versus an unmulched control. Researchers in Colombia compared strawberry growth under several different colors including red and a black control. Plants grown under red mulch outperformed plants using black mulch in areas such as fruit yield and berry quality (Casierra-Posada et al., 2011). In South Carolina, Kasperbauer (2000) also reported greater yield and berry size for red versus black mulch. By minimizing the differences in soil temperatures under the red and black mulch, it was suggested that the altered reflection spectra were responsible for the differences between the red-mulched and black-mulched plants. Later, Kasperbauer et al. (2001) reported that the altered radiation reflected by the red mulch led to berries that were higher in organic acids, aroma compounds, and sugar concentration.

Researchers in Iran found strawberries grown with red mulch were higher in anthocyanin and flavonoid content. However, they found no significant difference in total fruit weight produced over one growing season between black, white, and red mulches (Shiukhy et al., 2015). Plastic film of different colors have been shown to affect yield, appearance, nutritional compositions, and taste of strawberry fruit (Casierra-Posada, 2011; Kasperbauer, 2000; Kasperbauer et al., 2001; Locascio et al., 2005; Miao et al., 2017). Miao et al. (2017) reported that colored films, including red, yellow, green, blue, and white, affected fruit quality and bioactive compounds but have no effect on average individual fruit weight of strawberry. Red plastic film reflected more red and far red light, affected biosynthesis of anthocyanins, and resulted in the highest content of anthocyanins, flavonoids, phenolics, and antioxidant capacity among all tested colored films (Loughrin and Kasperbauer, 2002; Miao et al., 2017; Siegelman and Hendricks, 1958). Wang et al. (1998) found no difference in the yields, fruit size or soluble solids content of fruit from plants grown with black versus red plastic mulch.

Alternative production systems

While commercial strawberry production in the U.S. is primarily using annual hill system featuring raised beds and plasticulture, some strawberries are being grown in the old matted row and other alternative production systems. Containers such as bags, pots, and hanging bed with soilless substrate have been used for strawberry cultivation (Cantliffe et al., 2007), which takes place in open fields or combined with protective structures such as high tunnels and greenhouses. Vertical hydroponic systems have been used in high tunnels to make greater use of the space enclosed by the tunnel (Wortman et al., 2016). Soilless media affect plant growth characteristics and nutrient uptake (Wortman et al. 2016). Strawberry cultivars may vary in their growth response to different types of substrate. Strawberries grown in soilless substrate were reported to produce yields comparable or higher than strawberry plants in open fields (Recamales et al., 2007; Voća et al., 2006). Growing strawberries in soilless substrate alleviates the need for extensive soil management and fumigation. However, the high production cost may only be justified by high prices for off-season strawberries.

High Tunnels and their Applications in Small Fruit Production

High tunnels are a form of protected agriculture. The use of high tunnels in agricultural production is increasing in most areas of the world due to the abilities of the tunnels to protect crops and extend growing seasons into early spring and late fall. Other advantages of high tunnels are relatively low startup costs and increased quality and yield of crops. There is also the possibility of additional advantages such as disease and pest control (Janke et al., 2017). A high tunnel relies on passive heating and cooling of its interior unlike greenhouses which are climate controlled. Specifics of high tunnel construction vary widely according to intended use and other factors. They are constructed with metal or pvc frames covered with polyethylene films and (Janke et al. 2017; Lamont, 2009). High tunnels can be placed directly on field soil or be used with raised beds or hydroponics and can be semi-permanent or moveable. Sizes of high tunnels can vary considerably. A typical tunnel might be 6 to 10 feet wide and 96 feet long. Tunnels can be constructed as single bay or multi-bay and larger tunnels can have removable ends to allow access for tractors or other equipment. A high tunnel of 30 × 95 ft typically costs $7,000 to $9,000, with unit price ranging from $2.25 to $5.00 per square foot, which can often be justified by high market prices from off-season crops (Li and Bi., 2019; Robbins and Gu, 2018).

Worldwide, many different horticulture crops such as vegetables, small fruit, and cut flowers are grown in high tunnels (Lamont, 2009). There has been increasing interest from growers in the U.S. to produce a variety of specialty crops. High tunnels are used primarily for growing season extension and crop protection. The microenvironment in a high tunnel is generally hotter with than the outside environment. Average daily air temperatures inside high tunnels were 0.7 to 4.2 °C higher than outdoors. (Li and Bi, 2019). Depending on the month, average daily maximum temperatures can be up to 17 °C higher (Janke et al. 2017; Kadir et al., 2006; Wien, 2009). Both et al. (2007) reported 9% higher nighttime air temperature.

Due to reduced transmittance from the plastic covering, daily light integrals are decreased by about 25% in a tunnel compared to the outside environment (Both et al., 2007; Olberg and Lopez, 2016). Others have found even greater reductions (Jayalath et al., 2017). Zhao and Carey (2009) found decreases in photosynthetically active radiation (*PAR*) in the tunnel range from 16 to 36% lower than outside. There are conflicting reports in the case of relative humidity. Studies have reported relative humidity levels 10% to 15% higher than the surroundings (Both et al., 2007). However, Jayalath et al. (2017) had monthly average relative humidities up to 2% lower inside tunnels and Zhao and Carey (2009) found virtually no difference in relative humidity between the tunnel and surroundings. Li and Bi (2019) had many months with lower relative humidity inside a tunnel.

High tunnels can increase frost-free days, extend growing season into late fall or early spring, and introduce considerable market edge for off-season crops (Kadir et al., 2006; Lamont et al., 2002; Wells, 1996). High tunnels are reported to advance blueberry (*Vaccinium* spp.) harvests for 4 to 5 weeks compared to local open-field production (Jett, 2007; Kadir et al., 2006; Li and Bi, 2019; Rowley et al., 2010). High tunnels enabled early planting of red raspberry (*Rubus idaeus*) and blackberry (*Rubus* subgenus *Rubus*.). High tunnels have been used in many different parts of the country to extend the season for strawberries. High tunnels in North Carolina produced two to three weeks early (Ballington et al., 2008) In Kansas, high tunnel strawberries produced fruit a month before open field plants (Kadir et al., 2006).

Due to the exclusion of rain, high tunnels reduce disease pressure and improve fruit quality in a number of crops including strawberries, blueberries, grapes (*Vitis vinifera*), and caneberries (Ames, 2017; Demchak, 2009; Kadir et al., 2006; Li and Bi, 2019). Demchak (2009) found that disease incidence was lessened for small fruits grown in high tunnels compared with conventional field production. In their studies of raspberries grown in high tunnels, Leach et al. (2017) found that applied insecticides degraded more slowly in tunnels covered with ultraviolet reducing plastic. This allowed fewer applications of insecticide and longer interval between sprayings. However, there is research finding that the protected microclimate of a high tunnel can encourage pest populations. Researchers comparing tomato (*Solanum lycopersicum*), broccoli (*Brassica oleracea var. italica*) and cucumber (*Cucumis sativus*) grown under tunnels to those grown in open fields found higher insect pest pressure in the high tunnels and that many more insecticide applications were necessary than for the field crops. They suggested that the insect pests might benefit as much as the plants from protection from the elements (Ingwell et al., 2017).

Many crops grown in high tunnels are higher in yield and quality than their open field counterparts (Carey et al., 2009; Janke et al., 2017; Kadir et al., 2006). High tunnel increased total yield and marketable fruit of raspberry and blackberry compared to field production (Carey et al., 2009; Demchak, 2009; Kadir et al., 2006). Berry weight and per plant yields comparable to field grown plants were obtained even when strawberries were planted a month later than optimal for field planting (Demchak, 2009). Kadir et al. (2006) found that, in addition to earlier production, ‘Chandler’ and ‘Sweet Charlie’ strawberry plants produced more and larger fruit than the same cultivars grown in open fields. The high tunnel plants also produced fruit with a higher concentration of soluble solids.

Irrigation Management

Irrigation is one of the most important aspects of any growing operation. Efficient water usage has important economic and environmental consequences. An efficient irrigation program should be economically sound and reduce excessive nutrient leaching to ground water. This is especially true with container-grown plants since the growing substrate has a limited water holding capacity. Cylic irrigation involves splitting up the volume of water delivered to the plants into separate watering events as opposed to delivering the entire volume in a single time period. Fare et al. (1994) explored this practice on container grown holly (*Ilex crenata* Thunb. ‘Compacta’). Cylic irrigation reduced both the water runoff from the plants and the concentration of nitrate leached from the substrate. However, cylic irrigation had no significant effect on vegetative growth characteristics. Irrigation applied in split intervals increased plant growth, CO_2 assimilation, stomatal conductance, and water use efficiency of *Cotoneaster dammeri* ‘Skogholm’ compared with plants receiving water once in the morning (Warren and Bilderback, 2002).

Increasing irrigation frequency can improve growth and plant nutrient uptake by continually resupplying nutrient solution to the depletion zone around the roots. In their experiments with lettuce (*Lactuca sativa* L., cv. Iceberg), Silber et al. (2003) found that higher irrigation frequency led to more vegetative growth and higher concentrations of less mobile nutrients. Scagel et al. (2011; 2012) reported that increased irrigation frequency decreased water stress, increased nitrogen use efficiency, and had varying effects on mineral nutrient uptake of three *Rhododendron* species. The researchers found no increase in total biomass of the plants but a difference in water stress appeared to lead to a difference in resource allocation between different plant organs. Li et al. (2018) found that increasing irrigation frequency from once to twice per day decreased plant growth index, root dry weight, length, surface area, and flower number per plant in *Rhododendron sp*. 'Chiffon'. Deficit irrigation increased concentrations of taste- and health-related compounds including sugars and acids in strawberry fruit but resulted in smaller fruit size (Bordonaba and Terry, 2010).

Conventional vs. Organic Fertilization in Strawberry Production

There has been strong consumer demand for locally, sustainably, or organically grown fruits and vegetables with increasing consumer health consciousness (Olsson et al., 2006; Reganold et al., 2010; Strik et al., 2016). Organically grown strawberry fruit were found to have lower pesticide residues, better fruit quality, and greater antioxidant activity (Reganold et al., 2010). Olsson et al. (2006) found that the organically grown strawberries contained higher antioxidant levels than the conventionally grown berries even in the same cultivars ('Honeoye' and 'Cavendish') grown under the two different conditions. In addition, they found that extracts of the organically grown berries had a significantly greater inhibitory effect on cancer cells in vitro. By comparison, Hargreaves et al. (2008) found no significant differences in yield, total soluble solids content or antioxidant capacity in organically versus conventionally grown strawberries. Similar flavanol and phenolic acid contents were found in berries grown organically and conventionally by Häkkinen and Törrönen (2000).

Rysin et al. (2015) conducted a study of the economic aspects and environmental impacts of three versions of open field cultivation. Strawberries were grown in either conventional conditions, conditions with non-fumigated soil and added compost, or government approved organic growing conditions. The organic system had higher costs than the convention practices but also resulted in a higher profit. There was also a benefit with the organic system in that much less chemical fertilizer was used so the environmental impact of chemical runoff was greatly reduced (Rysin et al., 2015). Macit et al. (2007) tested five short day cultivars under organic and conventional conditions. The conventional treatments produced earlier flowering, earlier fruiting and a higher yield than the organically grown. However, some cultivars performed well under both conditions.

Fertilization practice is an important aspect in different production systems. Matching nutrient availability with plant requirements is especially important. Strawberries need different nutrient levels at different points in their growth cycle (Tagliavini et al., 2004). Conventional fertilizer provides nutrients in forms readily available for uptake by plants. Use of conventional fertilizer in slow and controlled release forms supplies nutrients over weeks or months. Controlled release fertilizer consists of polymer coated granules that allow a slow, regular release of fertilizer by diffusion at a rate determined by the composition and thickness of the coating (Havlin et al., 2013).

Organic fertilizers come from various animal or plant sources. The nutrient levels are generally lower than in the conventional fertilizers so that much greater amounts must be used.

The nutrients in organic fertilizer are incorporated in organic molecules that are not readily available to the plant. Mineralization must take place with microorganisms breaking down the organic molecules into plant available forms (Havlin et al., 2013). Therefore, the nutrients in organic fertilizer are slowly released with a rate that is dependent on the microbial population. This can be especially important in soilless growing systems because of differences in microbial communities between substrates (Grunert et al., 2016). There is potential for problems if the timing of fertilization doesn’t allow for sufficient nutrient release at critical points in the plants growth cycle (Pokhrel et al., 2015).

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CHAPTER II

HIGH TUNNEL PRODUCTION OF STRAWBERRIES USING BLACK AND RED PLASTIC MULCHES

Abstract

High tunnels are an economical season extension tool for strawberry (*Fragaria ×ananassa*) growers in non-major strawberry producing states in the United States (U.S.), where grower competitiveness can be increased by off-season fruit production. Six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars, were evaluated for their yield, quality, and time of fruit harvest in a high tunnel production system in Mississippi (USDA hardiness zone 8a). A red-colored plastic mulch was compared to the traditional black plastic mulch in strawberry production. The high tunnel raised daily air temperatures, provided frost protection, and resulted in first ripe fruit between 4 Mar. and 14 Mar. 2018, 4 to 6 weeks earlier than local field production. ‘Camino Real’, ‘Chandler’, and ‘Strawberry Festival’ produced similar highest total marketable yields of 482.9 g to 559.4 g per plant, with ‘Sensation’ producing the lowest marketable yield of 215.2 g per plant. Red mulch decreased marketable yield in March but increased it in May compared with the black mulch. Mulch type did not affect plant vegetative growth, or strawberry fruit quality variables including berry size, soluble solids content, total phenolic content, or total anthocyanin content.

Introduction

Strawberry is one of the most consumed fruits in the U.S., serving as an important component of a healthy diet (Giampieri et al., 2012). In 2017, total strawberry production in the U.S. was 1.6 billion tons, of which 1.3 billion pounds were fresh market strawberries, valued at \$3.5 billion, second only to commercial apple (*Malus ×domestica*) (AgMRC, 2019; Samtani et al., 2019; Shahbandeh, 2019a; USDA, 2019). Strawberries are valued for their taste and basic nutrition, and are rich in bioactive compounds such as anthocyanins, quercetins, and catechins, with benefits of slowing down aging, preventing cardiovascular diseases, inflammation, and certain types of cancers (Giampieri et al., 2012, 2014; Miao et al., 2017). Per capita consumption of fresh strawberries increased from 2 lb in 1980 to 7.2 lb in 2018 (AgMRC, 2019; Shahbandeh, 2019b; USDA, 2014).

Compared to major strawberry producing states California and Florida, producing 91% and 8% of strawberries in the U.S. (USDA, 2019), strawberry production in midsouthern states accounts for 0.5% of total U.S. production and occurs mainly on small- to medium-sized farms often diversified with other vegetable crops (Samtani et al., 2019). Locally sourced fresh strawberries are receiving increased demand through market outlets including community-supported agriculture (CSA), farmer’s market, u-pick farms, and farm stands (Hokanson and Finn, 2000; Samtani et al., 2019). Strawberry harvests in these states fall between February through June with peak production typically in April and May (AgMRC, 2019; Samtani et al., 2019). Strawberry harvest from field production in Mississippi often starts in late April or early May (Lewis, 2014). Growers use mainly June-bearing cultivars including ‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Strawberry Festival’ among others with limited use of day-neutral cultivars due to excessive heat in the south (Fontenot et al., 2014).

High tunnels are economic season-extension tools, constructed with metal frames covered with polyethylene films without automatic heating or cooling systems (Lamont, 2009). They can increase frost-free days, extend the growing season into early spring or late fall, and introduce considerable market edges for off-season crop production (Kadir et al., 2006; Lamont et al., 2002; Wells, 1996). High tunnels are reported to advance strawberry harvest by 2 to 4 weeks and advance blueberry (*Vaccinium* spp.) harvests by 4 to 5 weeks compared to local open-field production (Jett, 2007; Kadir et al., 2006; Li and Bi, 2019; Rowley et al., 2010). High tunnels enable early planting and increase total yield and marketable fruit of red raspberry (*Rubus idaeus*) and blackberry (*Rubus* subgenus *Rubus*) significantly compared to field production (Carey et al., 2009; Demchak, 2009; Kadir et al., 2006). Due to the exclusion of rain, high tunnels can reduce disease pressure and improve fruit quality in a number of crops including strawberries, blueberries, grapes (*Vitis vinifera*), and caneberries (Ames, 2017; Demchak, 2009; Kadir et al., 2006; Li and Bi, 2019). Unit price of a high tunnel ranges from $2.25 to $5.00 per square foot, which is often justified by high market prices from off-season crops and can be recovered over 1 to 5 years (Li and Bi, 2019; Robbins and Gu, 2018). There has been increasing interest from growers in the U.S. to produce a variety of specialty crops using high tunnels (O'Connell et al., 2012).

Commercial strawberry production in the U.S. mainly uses annual hill production (AHP) systems with plasticulture (California Strawberry Commission, 2018; Poling, 2015). Black plastic film are extensively used in an AHP system to increase soil temperature and moisture, aid with weed control, advance fruiting, and increased crop yield and quality (Lamont, 1993). Plastic film of different colors other than black has also been shown to affect yield, appearance, nutritional composition, and taste of strawberry fruit (Casierra-Posada et al., 2011; Decoteau et al., 1989; Kasperbauer, 2000; Kasperbauer et al., 2001; Locascio et al., 2005; Miao et al., 2017). Miao et al. (2017) reported that colored films, including red, yellow, green, blue, and white, affected fruit quality and bioactive compounds but had no effect on average individual fruit weight of strawberry. Red plastic film resulted in the highest content of anthocyanins, flavonoids, phenolics, and antioxidant capacity in strawberry fruit among tested colored films (Miao et al., 2017). Red film reflects more red and far red light and therefore may increase biosynthesis of bioactive compounds (Loughrin and Kasperbauer, 2002; Siegelman and Hendricks, 1958). The effect of red plastic mulch on strawberry yield and quality in a high tunnel production system merits further investigation.

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

Materials and Methods

Plant cultivation and management.

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

Since the heavy clay soil in the high tunnel was not suitable for growing strawberries, composted pine bark was introduced to the tunnel to build five raised beds (27.4 m long, 90 cm wide at the base, 60 cm wide at the top, and 15 cm high, spaced 1.2 m center-to-center), serving as five replications (blocks). Granular lime at a rate of 2.96 $kg \cdot m^{-3}$ (Soil Doctor Pelletized Lawn Lime; Oldcastle, Atlanta, GA) and micronutrients [containing 6% calcium (Ca), 3% magnesium (Mg), 12% sulfur (S), 0.1% boron (B), 1% copper (Cu), 17% iron (Fe), 2.5% manganese (Mn), 0.05% molybdenum (Mo), and 1% zinc (Zn)] at a rate of 0.89 $kg \cdot m^{-3}$ (Micromax; ICL Specialty Fertilizers, Summerville, SC) were incorporated into each raised bed before planting. A controlled release fertilizer 14N-6.1P-11.6K (Osmocote® 14-14-14, 3-4 months; ICL Specialty Fertilizers, Summerville, SC) was incorporated into the raised beds pre-planting at 5.04 $kg \cdot m^{-3}$.

Six June-bearing cultivars (Camarosa, Camino Real, Chandler, Fronteras, Strawberry Festival, and Sensation) and two day-neutral cultivars (Albion and San Andreas) were tested in this study. Plugs of the eight selected cultivars were purchased from Triple J Nursery (Hayden, AL). Strawberry plugs were transplanted into the raised beds in staggered double rows 30 cm between plants and 30 cm between rows on 18 Nov. 2017. The raised beds were covered with either a black plastic mulch (0.03 mm) or a red plastic mulch (0.03 mm) before planting (Filmtech Corp., Allentown, PA). This experiment used a split-plot design with a factorial arrangement of treatments and five replications. Strawberry cultivar served as the main plot factor and was randomly distributed within a block. Within each main plot, the color of plastic mulch, red or black, served as the sub-plot factor. There are ten single-plant subsamples in each sub plot.

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

Microenvironment in the high tunnel.

Environmental conditions including air temperature, relative humidity (RH), and photosynthetically active radiation (*PAR*) were recorded in the high tunnel. A data logger (HOBO USB Micro Station H21-USB; Onset Computer Corp., Bourne, MA) was installed in the center of the high tunnel. A temperature and RH sensor (HOBO S-THB-M002; Onset Computer Corp.) and a quantum sensor (HOBO S-LIA-M003; Onset Computer Corp.) were connected to the data logger to monitor air temperature, RH, and *PAR* at 15-min intervals. Daily light integral (DLI) was calculated by averaging *PAR* readings during a given day and multiplying 0.0864 as described by Torres and Lopez (2010). Local outdoor air temperature and RH data in Starkville were obtained from the website of the USDA-Natural Resources Conservation Service (USDA-NRCS, 2019). Growing degree days (GDDs) were calculated daily by [(Daily maximum temperature + daily minimum temperature)/2 – base temperature]. Cumulative GDDs between certain time periods were estimated by summing daily GDDs. The base temperature used for strawberry was 3 °C (Krüger et al., 2012).

Strawberry harvest.

Strawberry fruit was harvested twice weekly when ripe fruit were produced. The date when each plant produced the first ripe fruit was recorded. Strawberries were culled for misshapen, disease- or insect-damaged fruits. Strawberry fruit below 10 g was also considered unmarketable yield as described by Whitaker et al. (2015). Strawberry yield, marketable and unmarketable, and the number of berries produced per plant were recorded at each harvest. Size of strawberry fruit was estimated by single berry weight and calculated by dividing berry yield per plant by the number of berries. Total berry yield per plant was calculated by summing yield of all harvests during the growing season.

Plant vegetative growth.

Upon completion of fruit harvest in June 2018, two plants from each plot were randomly selected to evaluate vegetative growth including PGI {[plant height + widest width 1 + width 2 (width at the perpendicular direction to width 1]/3}, number of crowns per plant, and relative leaf chlorophyll content measured as Soil-Plant Analysis Development (SPAD) readings. Leaf relative chlorophyll content was measured on three fully expanded leaves, at the terminal leaflet of each leaf, using a chlorophyll meter (SPAD 502 Plus; Konica Minolta, Inc., Osaka Japan). Three readings measured from the selected leaves, one reading at each leaf, were averaged to represent relative chlorophyll content of a given plant. Above ground shoots of two plants, randomly selected from each plot, were then destructively harvested on 26 June 2018. Each harvested shoot sample was measured for fresh weight. Shoot samples were then oven-dried at

60 °C until no change in weight was observed. Dry weight of each shoot sample was also measured.

Fruit firmness, soluble solids content (SSC), and titratable acidity (TA).

Strawberry fruits from each cultivar grown with each mulch type were analyzed for quality variables including fruit firmness, SSC, and TA using fresh marketable berries. Two fruits from each plant, harvested on 7 May and 16 May respectively, were used to measure fruit firmness. Fruit firmness, measured at the widest part of a given fruit approximately one third of the fruit body close to the calyx end, was assessed as the maximum penetrating force (g) during tissue breakage with a digital fruit firmness tester and a 2-mm diameter tip (FR-5120; Lutron Electronic Enterprise CO., LTD, Taipei, Taiwan) (Nguyen et al., 2020). Soluble solids content was measured using marketable fruit from each plant. Selected fruit was sliced into halves, and juice was manually squeezed onto a digital refractometer (PR-32α; Atago U.S.A., Inc., Bellevue, WA) for SSC readings. Titratable acidity of strawberry fruit was measured using an automated titrator (EasyPlus; Mettler Toledo, Columbus, OH). For each replication, a composite sample containing approximately 50 g fruit (3 to 4 berries) from each sub-plot was used for TA measurement. Three subsamples were tested from each replication. For each TA measurement, 5 ml of juice was diluted with 80 ml of deionized water. The mixture was then titrated by 0.1 M NaOH to an end point of pH 8.2. Titratable acidity of strawberry fruit was expressed as percentage of citric acid equivalent (Cayo et al., 2016).

Juice preparation for bioactive compound analyses.

To measure bioactive compounds, a composite sample containing approximately 100 g marketable fruit from multiple plants in a replication was frozen at -20 °C until analysis.

Approximately 50 g of frozen strawberries were then thawed at 4 °C in a refrigerator and homogenized using a laboratory blender (7010G; Warning Commercial, Torrington, CT). Homogenized samples were then centrifuged (Centrifuge 5430 R; Eppendorf, Hamburg, Germany) at 7830 rpm, 4 °C for 20 min. Supernatant was collected from each sample and used for bioactive compound analyses including total phenolic content (TPC) and total anthocyanin content (TAC).

Total Phenolic Content

Total phenolic content of strawberry fruit was determined using the Folin-Ciocalteu (FC) method described by Singleton et al. (1999) with modifications. Three subsamples were tested from each replication. For each sample, 0.5 ml of strawberry juice was combined with 39.5 ml of deionized water and 2.5 ml of 10% Folin-Ciocalteu reagent (Sigma-Aldrich Co., St. Louis, MO, US). After 6 minutes, 7.5 ml of 20% sodium carbonate (Sigma-Aldrich Co.) was added to the mixture and the resulting solutions were left in darkness for 2 hours. The absorbance of the solution at 765 nm was measured by spectrophotometer (ThermoNicolet evolution 100; Thermo Scientific, Waltham, MA). Results are reported as mg gallic acid equivalents per liter (mg GAEs· L-1).

Total anthocyanin content.

The pH differential method was used to measure total monomeric anthocyanin content in strawberry fruit with modifications (Giusti and Wrolstad, 2001). Three subsamples were tested from each replication. For each sample, 300 µl of strawberry juice was added to 4.2 ml of pH 1.0 buffer (LabChem Inc., Zelienople, PA) and another 300 µl of strawberry juice was added to 4.2 ml of pH 4.5 buffer (LabChem Inc.). The resulting mixtures were allowed to equilibrate at room temperature for 15 to 30 minutes, and then tested for absorbance at 496 nm and 700 nm using a spectrophotometer (Thermo Nicolet Evolution 100; Thermo Scientific), respectively. The following formula was used to calculate the total monomeric anthocyanin content expressed as pelargonidin-3-glucoside (Pg-3-glc) equivalents: $TAC = (A \times MW \times DF \times 1000)/(\varepsilon \times 1)$. The absorbance A is calculated as: $A = (A_{496} - A_{700})_{pH1.0} - (A_{496} - A_{700})_{pH4.5}$. MW is the molecular weight of Pg-3-glc (433.4 $g \cdot mol^{-1}$); DF is the diluting factor of the buffers; ε is the molar absorptivity of Pg-3-glc (15600) according to Giusti et al. (1999); and 1 is the path length in cm. Total anthocyanin content was reported as mg Pg-3-glc equivalents$\cdot L^{-1}$, which was reported to be the predominant anthocyanin in strawberries (Tulipani et al., 2008).

Statistical analyses.

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

Results

Microenvironment in the high tunnel

Within the experiment duration from Nov. 2017 to June 2018, daily average air temperatures in the high tunnel ranged from 3.1 °C (on 17 Jan. 2018) to 30.7 °C (on 27 June 2018), compared to -8.33 °C to 29.44 °C outdoors on the same dates, respectively (Figure 2.1). The lowest daily minimum air temperatures of -12.5 °C in the high tunnel and -13.8 °C outdoors both occurred on 17 Jan. 2018. January 2018 was the coldest month during the study with the lowest monthly average temperature of 9.4 °C in the high tunnel and 3.9 °C outdoors. The highest daily maximum air temperatures were 37.5 °C in the high tunnel on 30 May 2018 and 34.4 °C outdoors on 27 June 2018. The high tunnel resulted in daily average temperatures up to 11.4 °C higher than the outdoor environment. The high tunnel increased daily minimum temperatures up to 2.1 °C and daily maximum temperatures up to 22.4 °C compared to outdoors within the experiment duration.

Daily average RH in the high tunnel ranged from 57% (on 31 Jan. 2018) to 96.5% (on 10 Jan. 2018), compared to outdoor environment ranging from 36% (on 3 Jan. 2018) to 98% (on 10 Jan. 2018) (Figure 2.2). In general, relative humidity in the high tunnel and outdoors fluctuated similarly during the growing season. Daily light integral in the high tunnel ranged from 4.52 (on 8 Nov. 2017) to 49.73 mol·m-2·d-1 (on 6 June 2018) within the experiment duration (Figure 2.3).

Plant vegetative growth

The eight tested strawberry cultivars varied in their vegetative growth in terms of plant growth index (PGI,) leaf SPAD readings representing relative leaf chlorophyll content, number of crowns per plant, fresh, and dry shoot weights (Table 2.1). Mulch type did not affect any tested variable mentioned above. Eight cultivars had relatively similar PGI with San Andreas (day-neutral) having the highest value of 34.7 cm and Albion (day-neutral) having the lowest of 29.9 cm (Table 2.2). ‘Albion’, ‘Camarosa’, ‘Camino Real’, ‘Fronteras’, and ‘San Andreas’ had comparable leaf SPAD readings ranging from 40.9 to 43.0, higher than ‘Chandler’, ‘Sensation’, or ‘Strawberry Festival’ with SPAD readings of 37.2 to 38.5. The eight cultivars had generally comparable number of crowns ranging from 3.5 to 5.4 per plant, with Albion having the lowest number of 3.5 per plant. Fresh and dry shoot weights of the eight cultivars were also generally similar, ranging from 72.7 g (in ‘Albion’) to 129.6 g (in ‘Strawberry Festival’) per plant, and from 27.3 g (in ‘Albion’) to 44.3 g (in ‘Strawberry Festival’) per plant, respectively. In general, there wasn’t a clear trend separating June-bearing from day-neutral cultivars in plant vegetative growth, which varied among all tested cultivars.

Fruiting time

Tested strawberry cultivars produced the earliest ripe fruit between 4 Mar. and 14 Mar. 2018 (Table 2.3). Black plastic mulch advanced ripening of strawberry fruit for 5 to 8 days in four cultivars including ‘Albion’, ‘Camarosa’, ‘Chandler’, and ‘Sensation’. The earliest cultivars were ‘Camarosa’ grown with black mulch and ‘Fronteras’ grown with either mulch type, producing the first ripe fruit on 4 Mar. and 6 Mar., respectively. Production of the first ripe strawberry fruit took place 106 to 116 days after transplanting and 1249.1 to 1374.3 GDDs for strawberry cultivars grown in a high tunnel.

Strawberry yield

During the 2017 to 2018 growing season, marketable strawberry yield of seven cultivars increased from March to May, peaked in May, decreased and ended in early June. The exception was ‘Chandler’ which peaked in April and declined slightly in May (Figure 2.4). ‘Camino Real’ and ‘Strawberry Festival’ produced the highest early marketable yields of 83.4 and 81.3 g per plant in March. ‘Chandler’, ‘Camarosa’, ‘Fronteras’, ‘Albion’, and ‘Sensation’ produced March yields of 34.3 g to 63.7 g per plant. In April, ‘Chandler’ and ‘Strawberry Festival’ produced the highest marketable yields of 212.8 g and 205.8 g per plant, respectively, higher than ‘Camarosa’, ‘Fronteras’, ‘Albion’, or ‘Sensation’ which produced marketable yields of 76.5 g to 165.9 g per plant. Five cultivars ‘Camino Real’, ‘Strawberry Festival’, ‘Albion’, ‘Fronteras’, and ‘Camarosa’ produced similar marketable yields in May ranged from 216.2 g to 257.8 g per plant, higher than ‘Sensation’ which produced 94.1 g marketable yield per plant. ‘Sensation’ had the lowest marketable yield among cultivars from March through May. ‘Fronteras’ produced the highest marketable yield of 35.0 g per plant in June, with all other cultivars having generally comparable marketable yield ranging from 13.2 g to 25.2 g per plant. ‘Camino Real’, ‘Chandler’, and ‘Strawberry Festival’ had similarly high total marketable yields of 559.4 g, 482.9 g, and 554.8 g per plant, respectively. ‘Albion’, ‘Camarosa’, ‘Fronteras’, and ‘San Andreas’ had comparable total marketable yield of 426.7 g to 474.6 g per plant. ‘Sensation’ had the lowest total marketable yield of 215.8 g per plant.

As for unmarketable yield, ‘Chandler’ produced significantly higher total unmarketable yield of 30.8 g per plant than any other tested cultivar, with ‘Camarosa’ producing the second highest total unmarketable yield of 16.6 g per plant (Figure 2.5). During the growing season, the highest unmarketable yield was produced in May in five cultivars, including ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘San Andreas’, and ‘Strawberry Festival’. Small fruits lower than 10 g per fruit were seen to be the main reason for unmarketable yields in ‘Chandler’. ‘Chandler’ also produced the least firm fruit among eight tested cultivars, causing unmarketable yield from mechanical damage during transport.

Compared to the red mulch, black mulch increased marketable yield by 11.2% in March, but decreased marketable yield by 9.7% in May (Table 2.4). Red mulch resulted in higher unmarketable yield than black mulch in March. There was an interaction between cultivar and mulch type in unmarketable yield in March and May, where red mulch increased unmarketable yield in ‘Chandler’ compared with black mulch, but resulted in similar unmarketable yields in other cultivars.

Fruit size and firmness

Strawberry fruit size in terms of single berry weight of marketable fruits measured on 1 May varied among cultivars, and was not affected by mulch type (Tables 2.1 and 2.5). ‘Albion’ and ‘Fronteras’ had the highest single berry weight of 24.0 g and 21.9 g per berry, respectively. ‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘San Andreas’, ‘Sensation’, and ‘Strawberry festival’ produced comparable single berry weights from 15.6 g to 19.7 g per berry. Strawberry fruit firmness was affected by the interaction between cultivar and mulch type (Table 2.1). ‘Albion’ and ‘Camarosa’, grown with either mulch type, ‘Sensation’ grown with black mulch, and ‘Strawberry Festival’ grown with red mulch produced strawberry fruit of greatest firmness ranging from 232.7 g to 247.7 g; firmer than those produced by ‘Camino Real’, ‘Chandler’, ‘Fronteras’, or ‘San Andreas’ with fruit firmness ranging from 145.1 g to 199.6 g (Fig. 2.6A). ‘Chandler’ produced the least firm fruit of 147.5 g or 145.1 g grown with black or red mulch, respectively. In general, the two mulch types resulted in similar fruit firmness except that black mulch increased fruit firmness in ‘Sensation’ by 16.7% compared to the red mulch.

Soluble solids content and titratable acidity

Fruit SSC was affected by cultivar but not by mulch type (Table 2.1). ‘Albion’ and ‘Sensation’ produced berries with the highest SSC of 10.0 °Brix and 9.9 °Brix, respectively, higher than any other cultivar (Table 2.5). ‘Camarosa’ and ‘Camino Real’ produced berries of the lowest SSC of 8.1 °Brix and 7.5 °Brix, respectively.

Titratable acidity in strawberry fruit was affected by the interaction between cultivar and mulch type (Table 2.1). In general, 'Albion' and 'Chandler' produced fruit of higher TA than the other six cultivars, with 'Albion' fruit grown with red mulch having the highest TA of 0.95% (Fig. 2.6B). 'Chandler' grown with either mulch type and 'Albion' grown with black mulch produced fruits of the second highest TA of 0.89%. The other six cultivars produced strawberry fruits of 0.60% (in 'Strawberry Festival' grown with red mulch) to 0.81% (in 'Fronteras' grown with black mulch) TA. Red mulch resulted in 7.4% and 4.5% increased TA in 'Albion' and 'Sensation' compared to black mulch. However, black mulch increased TA in 'Camino Real', 'Fronteras', and 'Strawberry Festival' by 16.9%, 13.9%, and 25.3% compared to the red mulch, respectively.

Total phenolic content and total anthocyanin content

Bioactive compounds including TPC and TAC in strawberry fruit were affected by the main effect of cultivar, but not by mulch type (Table 2.1). 'Camarosa', 'Chandler', and 'Fronteras' had comparable highest TPC ranging from 593.86 to 603.8 mg GAEs· L^{-1} (Table 2.5). The other five cultivars including 'Albion', 'Camino Real', 'San Andreas', 'Sensation', and 'Strawberry Festival' had comparable TPC of 572.4 to 582.5 mg GAEs·L^{-1}. As for TAC, 'Camino Real' and 'Camarosa' produced strawberry fruits with the comparable highest TAC of 202.0 and 195.5 mg Pg-3-glc equivalents·L^{-1}, significantly higher than those in 'Albion', 'Fronteras', 'San Andreas', 'Sensation', or 'Strawberry Festival' ranging from 109.1 to 134.0 mg Pg-3-glc equivalents·L^{-1}.

Discussion

The high tunnel used in this study provided frost protection by increasing the daily minimum temperature by up to 2.1 °C. Ogden and van Iersel (2009) reported lower daily minimum temperature in a high tunnel compared to outdoors on a number of nights and therefore no frost protection from the high tunnel in Watkinsville, Georgia (USDA hardiness zone 8a), possibly due to smaller size tunnels (12 m by 6 m) compared to the one in this study (29.0 m by 9.1 m). Another reason could be the different management of high tunnels where their high tunnels were closed on a set date and remain closed afterward (Ogden and van Iersel, 2009). However, the high tunnel used in this study was only closed when the outdoor air temperature dropped below 4.4 °C at night, and was reopened when the temperature rose during the day. Such effect in increasing temperatures is similar to a previous study using high tunnels for blueberry production in the same area (Li and Bi, 2019).

Requirements for GDDs in strawberry cultivars from transplanting or anthesis to fruit production can be used to predict fruit ripening grown in different climates (Bethere et al., 2016; Krüger et al., 2012). Krüger et al. (2012) reported strawberry cultivars required 29 to 38 days, and corresponding 301 to 434 GDDs from anthesis to fruit harvest using 3 °C as the base temperature. Duration of fruit development was reported to be negatively related to daily average temperature. By increasing daily average air temperature up to 11.4 °C, the high tunnel accumulated approximately 430 more GDDs from transplanting in Nov. 2017 to fruit harvest in mid-March 2018 compared to GDDs calculated from outdoor temperatures, and advanced strawberry harvest up to 4 to 6 weeks compared to local field production which typically starts from late April or early May (Lewis, 2014). Optimal growth temperature for strawberry plants ranges from 15 to 26 °C varying among cultivars and developmental stages, with flower initiation favoring temperatures below 20 °C, and vegetative growth favoring higher temperatures of approximately 25 °C (Hancock, 1999). The high tunnel provided daily average air temperature of 15 to 26 °C from 14 Feb. to 9 May 2018. With maximum air temperatures exceeding 30 °C in early May, warm temperatures in this region become the limiting factor for strawberry production as reported by Samtani et al. (2019). Strawberry flowers were observed in the high tunnel in mid-January, but failed to develop into fruit due to freezing temperatures at the time.

Except for ‘Sensation’, total marketable yield per plant of the seven tested cultivars are in the consistent range with reported strawberry yields from various studies (Anderson et al., 2019; Ballington et al., 2008; Demchak, 2009; Yao et al., 2015). Local growers consider a satisfactory strawberry yield roughly 454 g (1 lb) per plant. Over the area of the high tunnel of 263.9 m^2 (2850 ft^2), the total marketable yield was equivalent to 1332.7 $g \cdot m^{-2}$. With satisfactory strawberry yield plus advanced fruit harvest by 4 to 6 weeks compared to local field production, the high tunnel has the potential to introduce significant profit margins for growers. The cultivar ‘Sensation’ had survival problems in this study, mostly during plant establishment, with a high mortality rate of 20% to 60% per plot, resulting in the lowest marketable yield among all tested cultivars. No issues of plant loss during establishment were observed with other cultivars.

Main quality components of strawberry fruits including fruit size, firmness, SSC and TA of tested strawberry cultivars in this current study were in a consistent range as reported by Casierra-Posada et al. (2011), DeVetter et al. (2017), and Gu et al. (2017). Strawberry visual quality including size, color, and absence of damage are traditionally most important in customer preferences, especially at the initial purchase (Hinson and Bruchhaus, 2008; Retamales and Hancock, 2012). While fruit firmness is one of the most important attributes of strawberry postharvest quality, customers responded positively both to “a berry that melts in your mouth” and “a firm berry that makes it home from the market” (Colquhoun et al., 2012). Colquhoun et al. (2012 53) considered sweetness and complex flavors to be the most important attributes toward customer’s ideal strawberry experience. With increasing demand for fresh local produce, customers are shown to be willing to pay higher prices for locally produced strawberries of better eating quality or fruits with less pesticide contaminant concerns (Colquhoun et al., 2012; Hinson and Bruchhaus, 2005). Satisfactory eating quality promotes subsequent purchase of berry fruits (Retamales and Hancock, 2012), which is valued at local market outlets.

Mulch color did not affect fruit quality variables including single berry weight and SSC, in agreement with Casierra-Posada et al. (2011) reporting that red and black plastic mulches were generally favorable and produced strawberries of close quality compared with other tested colored mulches, for example silver.

Structures including mulches, plastic tunnels, and colored nets alter light intensity and quality over the plant canopy (Shiukhy et al., 2015). Plastic mulches of different thermal and radiation properties may therefore affect yield, quality, and timing of fruit production. Biosynthesis of anthocyanins in plants is said to be promoted by a light spectrum of 640 to 670 nm, in the red light wavelength interval (Siegelman and Hendricks, 1958). Red plastic mulch reflected more red and far red light than black mulch, and therefore may potentially increase anthocyanin content in strawberry fruit (Loughrin and Kasperbauer, 2002). However, mulch type in this current study did not affect TPC or TAC in eight tested strawberry cultivars. Such results were consistent with Shiukhy et al. (2015) reporting similar phenolic content in strawberry ‘Camarosa’ grown with red or black plastic mulch in Iran. But Shiukhy et al. (2015) reported increased anthocyanins in ‘Camarosa’ fruit using red mulch compared to black mulch. Various reasons can cause the different results. For example, Shiukhy et al. (2015) grew strawberries in the open field versus a high tunnel production system used in our study. Local environment and fruit sampling method may also have affected anthocyanin content results.

Besides the effect on anthocyanin biosynthesis in strawberry fruit, red light can affect flower initiation and soil temperature. Takeda et al. (2008) reported that illuminating ‘Strawberry Festival’ with red light resulted in a significant reduction in flowering in fall. In the current study, red mulch reduced marketable strawberry yield early in the season in March but increased marketable yield in May. Red mulch was reported to lower soil temperature compared to black mulch in various reports (Casierra-Posada et al., 2011; Kasperbauer, 2000; Kasperbauer et al., 2001; Locascio et al., 2005). Such an effect might be negative for marketable yield in March when the daily average air temperatures were below 22.5 °C, but beneficial during May where maximum air temperatures were above 29 °C limiting production of new flowers. Locascio et al. (2005) also reported lower early yield of four strawberry cultivars using red mulch compared to black mulch when grown in Florida.

Conclusions

Compared to the local outdoor environment, the high tunnel used in this study increased daily minimum, average, and maximum air temperatures by up to 2.1 °C, 11.4 °C, and 22.4 °C, respectively, reduced the likelihood of frost incidence, and advanced fruit harvest by 4 to 6 weeks compared to typical local strawberry harvest in open field production. In the 2017 to 2018 growing season, ‘Camino Real’, ‘Chandler’, and ‘Strawberry Festival’ produced the comparable highest total marketable yields of 482.9 g to 559.4 g per plant, with ‘Sensation’ producing the lowest total marketable yield of 215.8 g per plant due to plant loss in establishment. Compared to the black plastic mulch, red mulch decreased marketable yield in March, but increased marketable yield in May. Mulch type did not affect vegetative growth of strawberry plants, or strawberry quality variables including single berry weight, SSC, TPC, or TAC.

Table 2.1 A summary of analysis of variance for the effects of strawberry cultivar, mulch type, and the interaction between cultivar and mulch on all tested variables including plant growth index (PGI), relative chlorophyll content, number of crowns per plant, fresh and dry shoot weights, total marketable and unmarketable fruit yield, single berry weight, fruit firmness, soluble solids content, titratable acidity, total phenolic content, and total anthocyanin content.

	Plant vegetative growth and total yields[z]						
	PGI	**Relative chlorophyll content**	**Number of crowns**	**Fresh shoot wt.**	**Dry shoot wt.**	**Total marketable yield**	**Total unmarketable yield**
P-value[y]	(cm)		(per plant)	(g per plant)	(g per plant)	(g per plant)	(g per plant)
Cultivar	<.0001	<.0001	0.0026	0.0079	0.0077	<.0001	<.0001
Mulch	0.87	0.99	0.45	0.28	0.14	0.67	0.12
Cultivar*Mulch	0.059	0.11	0.45	0.12	0.20	0.11	0.0002

	Strawberry fruit quality					
	Single berry wt.	**Fruit firmness**	**Soluble solids content**	**Titratable acidity**	**Total phenolic content**	**Total anthocyanin content**
P-value	(g per berry)	(g)	(°Brix)	(%)	(mg GAEs·L^{-1})	(mg Pg-3-glc equivalents·L^{-1})
Cultivar	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Mulch	0.57	0.30	0.25	<.0001	0.1538	0.31
Cultivar*Mulch	0.29	0.0007	0.22	<.0001	0.4395	0.454

[z] Six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars were grown with black or red plastic mulches in a high tunnel production system in Starkville, Mississippi from Nov. 2017 to June 2018.

[y] Data were analyzed by two-way analysis of variance (ANOVA) using the PROC GLMMIX procedure of SAS (version 9.4; SAS Institute, Cary, NC).

Table 2.2 Vegetative growth of six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars grown in a high tunnel in Starkville, Mississippi from Nov. 2017 to June 2018.

Cultivar	**PGI**[z] (cm)	**Relative chlorophyll content**	**Number of crowns** (per plant)	**Fresh shoot wt.** (g per plant)	**Dry shoot wt.** (g per plant)
Albion	29.9 c	42.9 a	3.5 b	72.7 b	27.3 b
Camarosa	32.8 abc	40.9 a	4.8 ab	101.7 ab	39.3 ab
Camino Real	31.0 bc	43.0 a	5.3 a	100.7 ab	38.6 ab
Chandler	33.0 abc	37.2 b	5.4 a	95.2 ab	37.1 ab
Fronteras	33.5 ab	42.8 a	4.8 ab	92.3 b	31.5 ab
San Andreas	34.7 a	42.5 a	4.0 ab	106.9 ab	39.6 ab
Sensation	32.7 abc	38.0 b	4.8 ab	107.6 ab	32.1 ab
Strawberry Festival	34.4 ab	38.5 b	4.8 ab	129.6 a	44.3 a
P-value[y]	<.0001	< 0.0001	0.0026	0.0079	0.0077

[z] Plant growth index (PGI) = [plant height + widest width 1 + width 2 (width at the perpendicular direction to width 1]/3

[y] Different lower case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$

Table 2.3 Date of first ripe fruit, days after transplanting (DAT), cumulative growing degree days (GDDs) required for the first ripe fruit from planting, time of peak yield, and peak yield on a half-month basis of eight strawberry cultivars grown with black or red plastic mulch in a high tunnel.

Cultivar	**Mulch**	**Date of first ripe fruit in 2018**	**DAT (d)**	**Cumulative GDDs from planting**[z]
Albion	Black	Mar. 9	111	1312.2
	Red	Mar. 14	116	1374.3
Camarosa	Black	Mar. 4	106	1249.1
	Red	Mar. 12	114	1345.8
Camino Real	Black	Mar. 13	115	1361.1
	Red	Mar. 13	115	1361.1
Chandler	Black	Mar. 7	109	1288.7
	Red	Mar. 13	115	1361.1
Fronteras	Black	Mar. 6	108	1278.5
	Red	Mar. 6	108	1278.5
San Andreas	Black	Mar. 12	114	1345.8
	Red	Mar. 7	109	1288.7
Sensation	Black	Mar. 7	109	1288.7
	Red	Mar. 14	116	1374.3
Strawberry Festival	Black	Mar. 8	110	1301.2
	Red	Mar. 7	109	1288.7

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

Table 2.4 Monthly marketable and unmarketable yields of strawberry cultivars affected by mulch type grown in a high tunnel in Starkville, Mississippi from Nov. 2017 to June 2018.

	Marketable Yield (g per plant)[z]		**Unmarketable Yield (g per plant)**	
Mulch	**March**	**May**	**March**	**May**
Black	63.7	201.8	0.7	5.3
Red	57.2	220.3	1.3	7.5
P-value[y]	0.03	0.018	0.018	0.037

[z] Means of a certain type of mulch was obtained by averaging data over eight tested strawberry cultivars.

[y] $P \leq 0.05$ suggests significant difference between means within a column indicated by Tukey's HSD test.

Table 2.5 Single berry weight, fruit soluble solids content, total phenolic content, and total anthocyanin content of six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars grown in a high tunnel in Starkville, Mississippi from Nov. 2017 to June 2018.

	Single berry wt[z] (g per berry)	**Soluble solids content** (°Brix)	**Total phenolic content**[y] (mg GAEs·L^{-1})	**Total anthocyanin content** (mg Pg-3-glc equivalents·L^{-1})
Albion	24.0 a	10.0 a	582.2 bc	128.6 cd
Camarosa	17.2 bc	8.1 cd	603.8 a	195.5 ab
Camino Real	17.1 bc	7.5 d	576.1 bc	202.0 a
Chandler	16.3 c	9.1 b	594.2 ab	159.9 bc
Fronteras	21.9 ab	8.4 c	593.8 ab	109.7 d
San Andreas	19.7 abc	8.7 bc	572.4 c	110.1 d
Sensation	19.3 abc	9.9 a	582.5 bc	109.1 d
Strawberry Festival	15.6 c	9.1 b	582.3 bc	134.0 cd
P-value[x]	<.0001	<.0001	<.0001	<.0001

[z] Single berry weight is calculated by dividing marketable strawberry yield harvested on 1 May by the number of marketable fruit.

[y] GAEs stands for gallic acid equivalents; Pg-3-glc stands for pelargonidin-3-glucoside.

[x] Different lower case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$

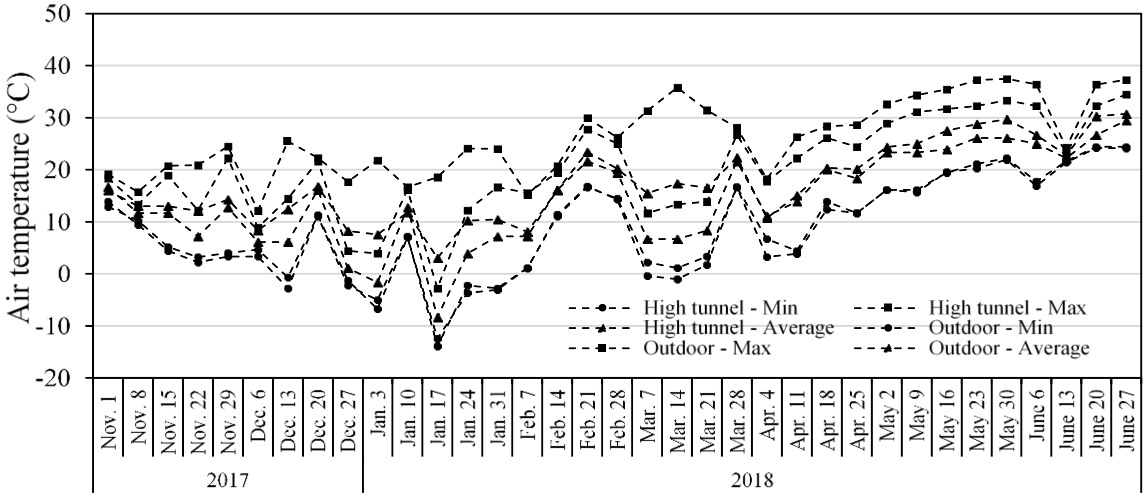

Figure 2.1 Daily minimum, average, and maximum air temperatures in the high tunnel and outdoors from Nov. 2017 to June 2018 in Starkville, Mississippi.

Air temperatures in the high tunnel were recorded by a temperature and relative humidity sensor (HOBO S-THB-M002; Onset Computer Corp.); Local outdoor air temperature data was obtained from the USDA Natural Resources Conservation Service website.

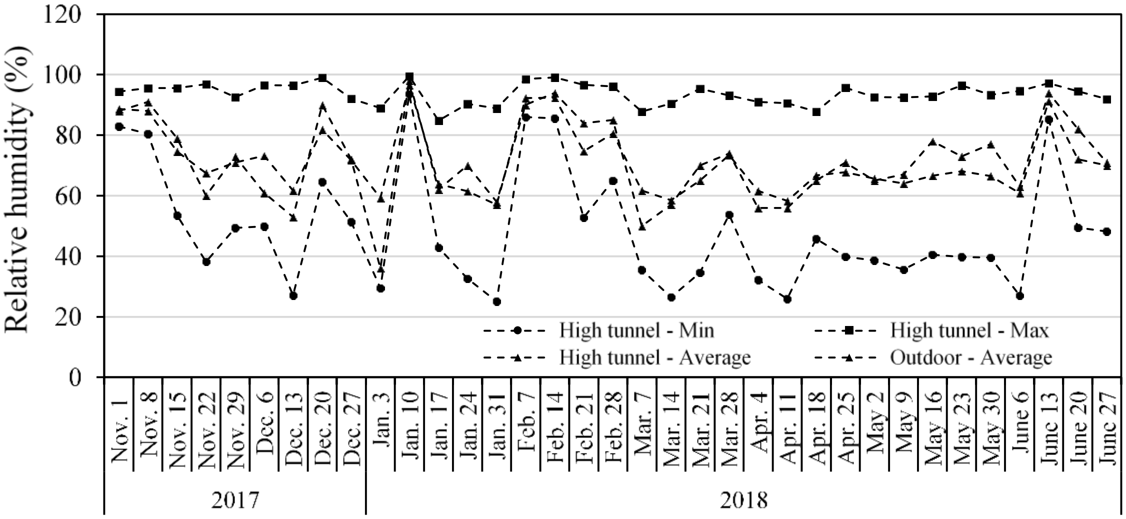

Figure 2.2 Daily minimum, average, and maximum relative humidity (RH) in the high tunnel and daily average RH outdoors from Nov. 2017 to June 2018 in Starkville, Mississippi.

Relative humidity in the high tunnel was recorded by a temperature and relative humidity sensor (HOBO S-THB-M002; Onset Computer Corp.); Local outdoor RH data was obtained from the USDA Natural Resources Conservation Service website

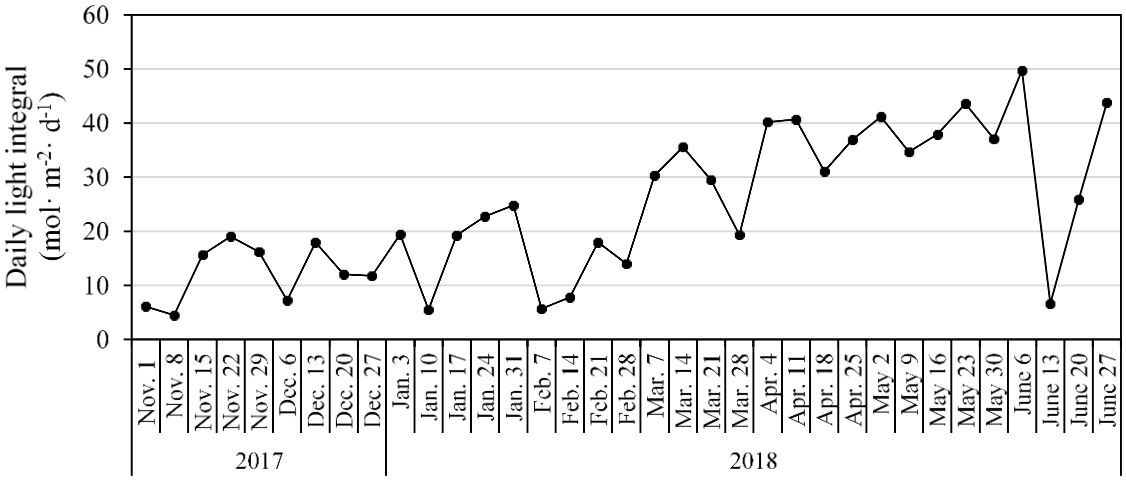

Figure 2.3 Daily light integral (DLI) in the high tunnel from Nov. 2017 to June 2018 in Starkville, Mississippi.

Daily light integral in the high tunnel was calculated by averaging photosynthetically active radiation (*PAR*) readings during a day and multiplying 0.0864 as described by Torres and Lopez (2010). *PAR* was recorded by a quantum sensor (HOBO S-LIA-M003; Onset Computer Corp.) at 15-min intervals connected to a data logger (HOBO Micro Station H21-002; Onset Computer Corp.).

Figure 2.4 Monthly and total marketable yield of Six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars grown with black or red plastic mulches in a high tunnel production system in Starkville, Mississippi from Nov. 2017 to June 2018.

Different lower case letters on top of each bar indicate significant difference in total marketable yield among cultivars using Tukey’s HSD test at $P \leq 0.05$.

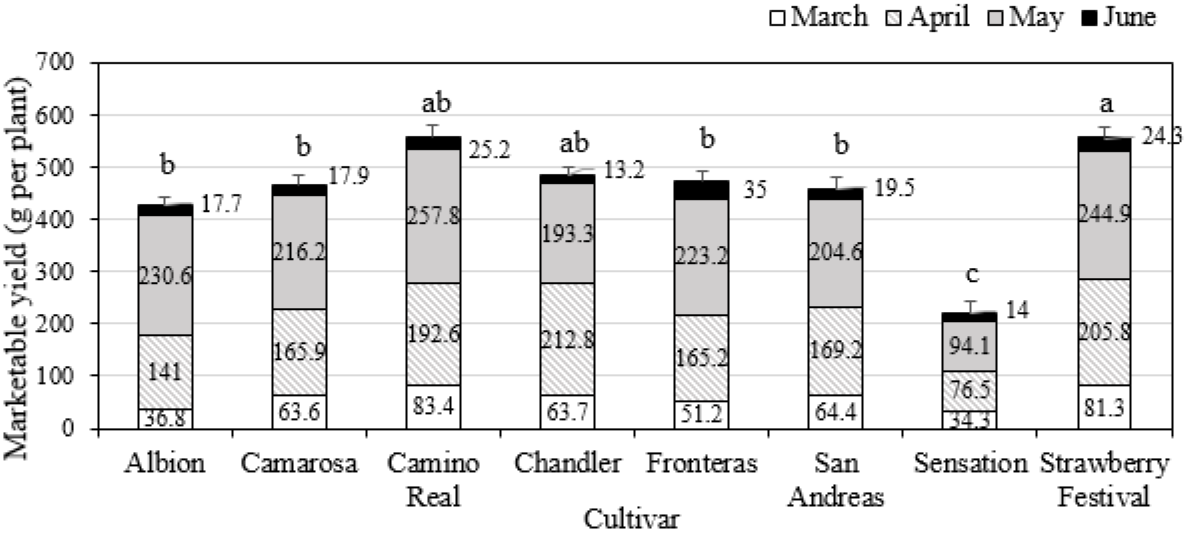

Figure 2.5 Monthly and total ummarketable yield of six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars grown with black or red plastic mulches in a high tunnel production system in Starkville, Mississippi from Nov. 2017 to June 2018.

Strawberry fruits that were misshapen, disease- or insect-damaged, or below 10 g were considered unmarketable yield. Different lower case letters on top of each bar indicate significant difference in total unmarketable yield among cultivars using Tukey’s HSD test at $P \leq 0.05$.

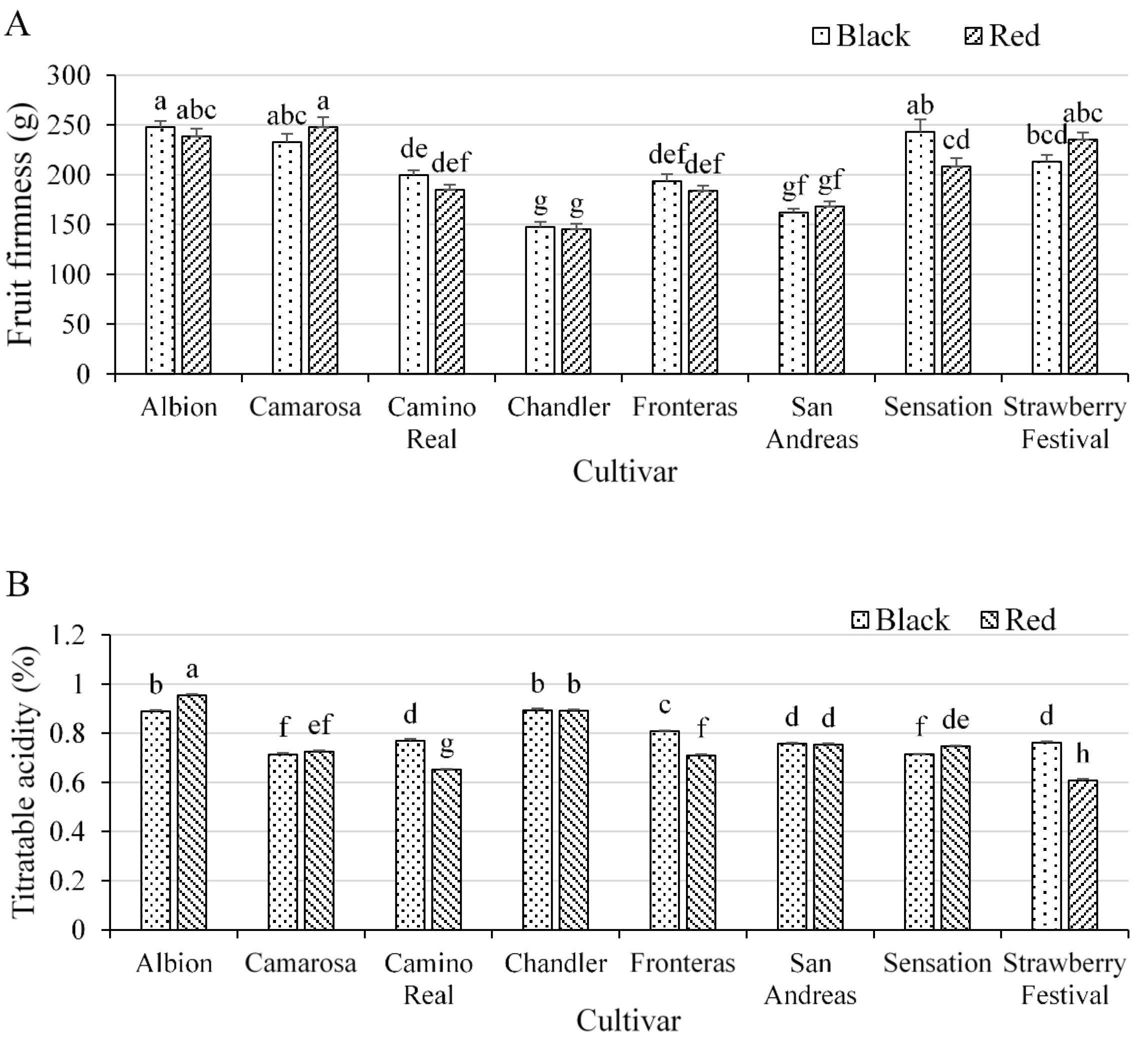

Figure 2.6 Strawberry fruit firmness (A) and titratable acidity (B) affected by the interaction between cultivar and mulch type grown in a high tunnel in Starkville, Mississippi from Nov. 2017 to June 2018.

Six June-bearing (‘Camarosa’, ‘Camino Real’, ‘Chandler’, ‘Fronteras’, ‘Sensation’, and ‘Strawberry Festival’) and two day-neutral (‘Albion’ and ‘San Andreas’) strawberry cultivars were grown with black or red plastic mulches in a high tunnel production system; Different lower case letters on top of each bar indicate significant difference among all treatment combinations using Tukey’s HSD test at $P \leq 0.05$

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CHAPTER III

FERTILIZER TYPE AND IRRIGATION FREQUENCY AFFECT PLANT GROWTH, YIELD, AND FRUIT QUALITY OF CONTAINERIZED STRAWBERRY CULTIVARS

Abstract.

Small-scale strawberry production in southeastern states require cultivars adapted to local climates. This study investigated plant growth, gas exchange, yield and fruit quality of ten strawberry (*Fragaria ×ananassa* Duch.) cultivars affected by fertilizer type and irrigation frequency in a containerized production system in 2018. Bare root liners of seven June-bearing and three day-neutral cultivars were grown in 2-gallon containers, fertilized with a conventional fertilizer or an organic fertilizer at comparable rates, and irrigated once or twice daily with the same total irrigation volume**.** Strawberry cultivars varied in vegetative growth (including plant growth index (PGI), leaf SPAD, number of crowns, visual score, and root dry weight) and fruiting characteristics (including first harvest date, yield, number of fruit, berry size, fruit soluble solids content, and firmness). Day-neutral cultivars ‘Evie 2’ and ‘Seascape’ produced the highest total yields and late-season yield in June. The conventional fertilizer resulted in higher PGI, leaf SPAD, plant visual score, fruit yield in May, daily water use, and net photosynthetic rate than the organic fertilizer. Two irrigations per day increased substrate moisture compared with one irrigation per day, and increased shoot dry weight with the conventional fertilizer application. Except for substrate moisture or shoot dry weight, irrigation frequency did not affect plant growth index (PGI), leaf SPAD, gas exchange, fruit yield, or quality in tested strawberry cultivars.

Introduction

The United States is the world's second largest producer of strawberries (*Fragaria ×ananassa* Duch.) (FAO, 2018). In 2017, U.S. produced 1.6 billion pounds of strawberries, with an industry value of near $3.5 billion, second only to apple (*Malus domestica* Borkh.) (AgMRC, 2019; Samtani et al., 2019). Strawberry is one of the most consumed fruits in the U.S., serving as an important component of a healthy diet (Giampieri et al., 2012). Per capita consumption of fresh strawberries increased from 2 lbs in 1980 to 7.2 lbs in 2018 (AgMRC, 2019; Shahbandeh, 2019; USDA, 2014). Strawberries are valued not only for basic nutritional components including sugars, mineral nutrients, and vitamins, but they are also rich in bioactive compounds that are known to have antioxidant capacity, scavenge free radicals, and introduce health benefits such as slowing down aging, preventing cardiovascular diseases, inflammation, and certain types of cancers (Giampieri et al., 2014; Miao et al., 2017).

Cultivated strawberry plants are classified into three types of cultivars based on their flowering response to photoperiods: June-bearing, everbearing, or day-neutral (Hancock, 1999). June-bearing strawberries initiate flowering in response to a short photoperiod of 14 hours or less, or low temperatures below 15 °C, and typically produce one flush of fruit in spring (Hancock, 1999; Husaini and Neri, 2016). Ever-bearing cultivars initiate flower buds with days of greater than 12 h, resulting in a fall harvest or two crops in one year (Gu et al., 2017). Day-neutral strawberry plants can produce crowns and flower buds whenever the temperature is within a favorable range of 4 to 29°C regardless of the day length (Rowley et al., 2011). This ability allows for potential year-round fruit harvest in areas where summer or fall temperatures stay in this range or where high tunnels or other protected cultivation methods can produce the favorable conditions (Rowley et al., 2011; Ballington et al., 2008). Commercial production of strawberries uses mostly June-bearing cultivars or a combination of June-bearing and day-neutral cultivars, with ever-bearing cultivars rarely grown outside of home gardens. There has been increasing interests in using day-neutral cultivars for extended harvest season (Samtani et al., 2019).

The leading states for strawberry production in the U.S. are California and Florida, producing approximately 91% and 8% of the nation's strawberry crop (USDA, 2019). Commercial strawberry production in the U.S. uses primarily an annual hill production system featuring plasticulture and raised beds. Strawberry production in all other states is mainly small-scale and aims for local market outlets (Samtani et al., 2019). Growers are seeking ways to improve competitiveness, including using protected culture with greenhouses, high and low tunnels, or soilless culture to achieve season extension, reduce pest pressure, and improve fruit yield and quality (Lieten, 2013; Samtani et al., 2019). In the state of Mississippi, strawberry production uses fall planting, whereas plant availability in a number of commercial nurseries starts in spring. Therefore, strawberry production in these areas are limited by the available strawberry cultivars. Research is needed to evaluate strawberry cultivars suitable to local subtropical climates.

There has been strong consumer demand for locally, sustainably, or organically grown fruits and vegetables with increasing consumer health consciousness (Olsson et al., 2006; Reganold et al., 2010; Strik et al., 2016). Organically grown strawberry fruit were found to have lower pesticide residues, better fruit quality, and greater antioxidant activity (Reganold et al., 2010). By comparison, Hargreaves et al. (2008) found no significant differences in yield, total soluble solids content or antioxidant capacity in organically versus conventionally grown strawberries. Similar flavanol and phenolic acid contents were found in berries grown organically and conventionally by Häkkinen and Törrönen (2000). Fertilization management is an important aspect of growing strawberry plants in an alternative production system. There lacks information regarding effects of certain organic growing practices like fertilizer type on plant growth, fruit yield and quality of strawberry plants.

An efficient irrigation program should be economically sound, and reduces excessive nutrient leaching to ground water. Deficit irrigation increased concentrations of taste- and health-related compounds including sugars and acids in strawberry fruit, but resulted in smaller fruit size (Bordonaba and Terry, 2010). Fare et al. (1994) reported that splitting the irrigation volume into separate times reduced water runoff and nitrate leached from the substrate in container grown holly (*Ilex crenata* Thunb. 'Compacta'). Scagel et al. (2011; 2012) reported that increased irrigation frequency decreased water stress, increased nitrogen use efficiency, and had varying effects on mineral nutrient uptake of three *Rhododendron* species. Irrigation applied in split intervals increased plant growth, CO_2 assimilation, stomatal conductance, and water use efficiency of *Cotoneaster dammeri* 'Skogholm' compared with plants receiving water once in the morning (Warren and Bilderback, 2002). Li et al. (2018) found that increasing irrigation frequency from once to twice per day decreased plant growth index, root dry weight, length, surface area, and flower number per plant in *Rhododendron sp*. 'Chiffon'. Plant species varied in their response to altered irrigation frequency. The effect of altering irrigation frequency on plant growth and fruit production of strawberry cultivars remains unclear.

We hypothesized that fertilizer type and irrigation frequency may affect strawberry plant performance independently or interactively in a container production system. The objective of this study was to investigate plant vegetative growth, gas exchanges, fruit yield and quality of ten strawberry cultivars, including seven June-bearing and three day-neutral, as affected by fertilizer type and irrigation frequency in USDA hardiness zone 8a.

Materials and Methods

Plant culture and treatments

Seven June-bearing cultivars ‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’, and three day-neutral cultivars ‘Evie 2’, ‘San Andreas’, and ‘Seascape’ were evaluated in this study. Bare-root liners of the ten selected cultivars were purchased from a commercial nursery (Nourse Farms, Whately, MA) and transplanted into 2-gallon plastic containers (C900, top diameter 24.1 cm, height 23.2 cm, volume 7.33 L; Nursery Supplies® Inc., Chambersburg, PA) on 28 Feb. 2018. Pine bark: peat moss: perlite in a volume ratio of 4:3:1 was used as growing substrate. The substrate was incorporated with 0.89 $kg \cdot m^{-3}$ micronutrient (Micromax®; ICL Specialty Fertilizers, Summerville, SC) and 2.97 $kg \cdot m^{-3}$ lime (Soil Doctor Pelletized Lawn Lime; Oldcastle, Atlanta, GA). Each containerized plant was fertilized with 60 g granular organic fertilizer 5N-1.3P-3.3K (5-3-4; McGeary Organics, Lancaster, PA) or 20 g conventional controlled-release fertilizer 15N-2P-10K (Osmocote® plus 15-9-12 5-6 months; Scotts Miracle-Grow Co., Marysville, OH). All strawberry plants were maintained outdoors in full sun at the R. R. Foil Plant Science Research Center of Mississippi State University in Starkville, MS (lat. 33.45° N, long. 88.79° W; USDA hardiness zone 8a). Strawberry plants were drip irrigated at a flow rate of 1.9 liters per hour with the same total daily irrigation volume through two irrigation frequencies: once per day at 0800 HR and or twice per day at 0800 HR (half volume) and 1430 HR (half volume). Plants were irrigated to replace daily water loss plus 10% to

15% leaching fraction. Irrigation volume was determined by randomly selecting ten plants and measure their daily water use approximately once per month.

Local outdoor air temperature in Starkville were obtained from the website of the USDA-Natural Resources Conservation Service (USDA-NRCS, 2020). Growing degree days (GDDs) were calculated daily by [(daily maximum temperature + daily minimum temperature)/2 – base temperature]. Cumulative GDDs between certain time periods were estimated by summing daily GDDs. The base temperature used for strawberry was 3 °C (28).

Plant growth and visual quality

Plant height and widths (width 1, the widest point of canopy; width 2, perpendicular width of width 1) of each plant were measured on 22 June 2018. Plant growth index (PGI) was calculated as the average of the plant height and two widths to estimate plant size. On 20 June, relative leaf chlorophyll content was estimated by SPAD readings. Leaf SPAD readings were measured from the terminal leaflet of three fully expanded new leaves using a chlorophyll meter (SPAD 502 Plus; Konica Minolta, Inc., Osaka Japan). An average of the three readings were calculated to represent relative leaf chlorophyll content of an individual plant. Plant visual quality was evaluated by a five-point scale, where 1= poor quality with severe leaf damage over 70%; 2= leaf damage of 50 to 70%, 3= moderate quality with 20 to 50% leaf damage; 4= good quality with minor leaf damage of less than 20%; 5=excellent quality without any leaf damage. A dead plant was rated 0 for the visual score.

One plant from each treatment combination was destructively harvested with three replications, randomly selected from three different blocks, on 3 July 2018. For each individual plant, shoots were separated from roots, and roots were then cleaned free of substrate. Roots and shoots samples were oven dried at 60 °C to constant weight. The number of crowns from each harvested plant and the dry weight of each sample were recorded.

Water use and substrate moisture

Daily water use (DWU) was determined in plants irrigated once per day using a gravimetric method by subtracting pot weight (plant included) 24 h after irrigation from pot weight at container capacity (about half an hour after irrigation). Daily water use was measured twice during the season on 19 June and 27 June, respectively. Substrate moisture at 6-cm depth was measured using a soil moisture sensor (ML2x; Delta-T Devices, Cambridge, England) with two readings collected from each container. The moisture sensor was connected to a soil sensor reader (HH2; Delta-T Devices) for instant moisture readings. Substrate moisture was measured on 27 June before scheduled daily irrigation started in the morning.

Gas exchange measurements.

To evaluate physiological activities of plants affected by fertilizer type and irrigation frequency, leaf net photosynthetic rate (Pn), stomatal conductance (g_s), and transpiration rate (Trmmol) of strawberry plants were measured between 1100 HR and 1500 HR on 27 June and 28 June using a portable photosynthesis system (LI-6400XT; LI-COR Inc., Lincoln, NE). Three plants were randomly selected from three different blocks for gas exchange measurements for each treatment combination. One recent fully expanded leaf, not shaded by other leaves, was selected for the measurement. The selected leaf was enclosed into a 2-cm^2 leaf chamber with a fluorometer (6400-40; LI-COR Inc.) as light source. A reference CO_2 concentration of 400 $\mu mol \cdot mol^{-1}$ and photosynthetically active radiation (*PAR*) of 1500 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were maintained inside the leaf chamber during gas exchange measurements. Block temperature was maintained according to outdoor air temperature on the measurement date.

Strawberry fruit harvest.

Strawberry fruit was harvested once per week. The date of first fruit harvest was recorded for each plant. Strawberries were culled for misshaped, disease- or insect-damaged fruits. Fruit yield and the number of fruit at each harvest were recorded. Yield from each harvest was summed for a season total. Soluble solids content of strawberry fruit from each plant were measured using a digital refractometer (PR-32α; Atago U.S.A., Inc., Bellevue, WA). Fruit firmness was measured with a fruit hardness tester (FR-5120; Lutron Electronic Enterprise CO., LTD, Taipei, Taiwan). One marketable fruit was used to measure soluble solids content and fruit firmness from each plant, respectively.

Experimental design and data analyses.

The experiment was designed in a factorial randomized complete block design with 5 replications. Three mains factors are strawberry cultivar (10), fertilizer type (2), and irrigation frequency (2), resulting in 40 treatment combinations. Each replication contained 2 single-plant subsamples. Due to the large number of treatment combinations, data of plant dry weights and gas exchange were measured with 3 replications, where the three plants were randomly selected from different blocks. Data were analyzed by analysis of variance (ANOVA) using the PROC GLIMMIX procedure in SAS (version 9.4; SAS Institute, Cary, NC). Where indicated by ANOVA, means were separated using Tukey's Honest Significant Difference (HSD) test at $P \leq 0.05$.

Results

Plant vegetative growth

Plant vegetative growth variables including plant growth index (PGI) ($P < 0.0001$), leaf relative chlorophyll content measured as leaf SPAD ($P < 0.0001$), number of crowns per plant

(*P*= 0.040), visual score (*P*< 0.0001), and root dry weight (*P*< 0.0001) varied among cultivars (Table 3.1), with PGI (*P*= 0.0003), SPAD (*P*< 0.0001), and plant visual score (*P*= 0.044) also affected by the main effect of fertilizer type without interactions (Table 3.2).

‘Allstar’, ‘Jewel’, and ‘Honeoye’ had comparable highest PGIs ranging from 40.9 to 41.6 cm, higher than ’Chandler’, ‘Evie 2’, or ‘San Andreas’ with the lowest PGIs of 37.0 to 37.6 cm (Table 3.1). The other four cultivars ‘Darselect’, ‘Earlyglow’, ‘L’Amour’, and ‘Seascape’ had similar PGIs of 38.3 to 39.5 cm. The three day-neutral cultivars ‘Evie 2’, ‘San Andreas’, and ‘Seascape’ had the comparable highest leaf SPAD ranging from 35.7 to 37.5, with ‘Allstar’, ‘Chandler’, ‘Darselect’, and ‘Jewel’ having the lowest SPAD readings ranging from 30.4 to 31.9. Ten tested cultivars generally produced similar number of crowns per plant averaged 3.5 to 5.2 per plant. ‘Honeoye’ had the highest visual scores averaged 3.8 with minor leaf damage. ‘L’Amour’, and ‘Seascape’ had intermediate visual scores of 3.2 and 3.3, respectively. ‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Evie 2’, ‘Jewel’, and ‘San Andreas’ had comparable visual scores ranging from 2.6 to 3.0 out of 5.

Shoot dry weight ranged from 58.8 g to 81.5 g per plant, similar among all tested cultivars. ‘Allstar’, ‘Darselect’, ‘Honeoye’, ‘Jewel’ and ‘L’Amour’ had comparable root dry weights of 12.9 g to 17.3 g per plant, with ‘Chandler’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’ having comparable root dry weights of 9.6 g to 12.9 g per plant (Table 3.1).

When affected by the main effect of fertilizer type, the conventional fertilizer increased PGI, SPAD, and visual score by 4.2%, 7.1%, and 14.3% compared to the organic fertilizer, respectively (Table 3.2). Fertilizer type did not affect other vegetative growth variables besides those reported in Table 3.2.

Affected by the interaction between fertilizer type and irrigation frequency (*P*= 0.049), strawberry plants fertilized with the conventional fertilizer and irrigated twice per day produced higher shoot dry weight of 81.8 g per plant than plants fertilized with organic fertilizer and irrigated twice per day, or plants irrigated once per day fertilized with the conventional or the organic fertilizer (Table 3.3). Irrigation frequency did not affect plant vegetative growth variables besides shoot dry weight.

Timing of fruit harvest.

When transplanted on 28 Feb. 2018, fruit harvest of tested strawberry cultivars started 49.4 days after transplanting (DAT) in ‘Honeoye’ to 65.7 DAT in ‘Chandler’ in the 2018 growing season (Table 3.4), with correspondent accumulative GDDs of 536 and 783 (Figure 3.1A), respectively. The day-neutral cultivar ‘Evie 2’ was the second latest-fruiting cultivar with the first harvest being 60.9 DAT. Local average daily air temperature was in between 12.8 °C to 23.6 °C during the first fruit harvest of tested cultivars (Figure 3.1B). Fertilizer type or irrigation frequency did not affect the fruit production timing of any tested cultivars. The first fruit harvest was on 19 Apr. and the last fruit harvest was on 13 June 2018 with a total of ten harvests.

Yield

In April, five cultivars Darselect, Earlyglow, Honeoye, San Andreas, and Seascape produced similar yield ranging from 17.9 g to 24.4 g fruit per plant, higher than ‘Allstar’, ‘Chandler’, or ‘Jewel’ (Table 3.5). In May, the two day-neutral cultivars Evie 2 and Seascape produced the highest and second highest yield of 170.6 g and 135.7 g fruit per plant, with ‘Chandler’, ‘Darselect’,‘Earlyglow’, ‘Honeoye’, and ‘L’Amour’ producing the lowest yield of 16.6 g and 50.2 g fruit per plant. The conventional fertilizer increased yield in May by 17.3% compared with the organic fertilizer (Table 3.2). In June, ‘Evie 2’ produced the highest yield of

56.8 g fruit per plant, with all other cultivars producing similar yield below 10 g fruit per plant. ‘Darselect’ and ‘Jewel’ did not produce any fruit in June. Except for the two early ripening cultivars Earlyglow and Honeoye producing peak harvest in April, the other eight cultivars produced peak harvest in May, which was 68% to 92% of total yield.

For total yield, the two day-neutral cultivars Evie 2 and Seascape ranked first and second producing yield of 236.3 g and 167.6 g per plant, respectively (Table 3.5). ‘Evie 2’ and ‘Seascape’ also produced the highest and the second highest fruit number of 16.5 and 12.3 per plant among all tested cultivars (Table 3.4). The seven June-bearing cultivars Allstar, Chandler, Darselect, Earlyglow, Honeoye, Jewel, and L’Amour generally produced similar total yield and number of fruit per plant ranging from 35.2 g to 65.8 g per plant and 3.1 to 6.9 fruits per plant, respectively.

Fruit quality.

The day-neutral cultivar San Andreas produced the largest berry size averaged 17.8 g per berry, higher than ‘Darselect’, ‘Evie 2’, or ‘Seascape’ producing berry size of 14.0 g to 14.8 g per berry. ‘Allstar’, ‘Earlyglow’, ‘Honeoye’, and ‘Jewel’ produced comparable lowest berry sizes of 8.8 g to 10.1 g per berry (Table 3.4).

‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, ‘L’Amour’, and ‘Seascape’ had comparable soluble solids content ranging from 10.3 to 11.1 °Brix, with ‘Evie 2’ and ‘San Andreas’ producing fruit with the lowest soluble solids content of 8.4 and 8.7 °Brix, respectively. ‘San Andreas’, ‘L’Amour’, and ‘Allstar’ produced the firmest strawberry fruit of 1.89 to 2.17 N, higher than ‘Chandler’, ‘Darselect’, ‘Earlyglow’, or ‘Evie 2’ producing the least firm fruit of 1.32 to 1.53 N (Table 3.4).

Fruiting characteristics including time of fruit harvest, strawberry yield, berry size, number of fruit per plant, fruit soluble solids content and firmness were not affected by fertilizer type or irrigation frequency.

Water use and substrate moisture

Daily water use was significantly different among cultivars on June 19 but similar among cultivars on June 26 ranging from 0.57 L to 0.78 L per day (Table 3.6). On June 19, eight cultivars had similar daily water use ranging from 0.54 L ('San Andreas') to 0.67 L ('Allstar'), with 'L'Amour' and 'Seascape' having the highest and lowest daily water use of 0.71 L and 0.53 L per day, respectively. Substrate moisture at 6-cm depth was generally similar among cultivars ranging from 23.1% in 'Darselect' to 28.0% in 'Allstar'. Organic fertilizer resulted in increased substrate moisture by 10.6% compared to the conventional fertilizer (Table 3.2). Two irrigations per day also increase substrate moisture by 44.0% compared to one irrigation per day (Table 3.3).

Gas exchange

Net photosynthetic rate (Pn) was the highest in 'L'Amour' of 14.4 μmol m^{-2} s^{-1}, similar to 'San Andreas' or 'Seascape', but higher than the other seven cultivars ranging from 9.7 to 11.2 μmol·m^{-2}·s^{-1} (Table 3.7). Stomatal conductance (g_s) was similar among all cultivars ranging from 0.072 mol·m^{-2}·s^{-1} in 'Darselect' to 0.14 mol·m^{-2}·s^{-1} in 'L'Amour' or 'San Andreas'. The conventional fertilizer increased Pn by 12.1% compared with the organic fertilizer (Table 3.2). 'San Andreas' had the highest transpiration rate (Trmmol) of 6.65 mmol·m^{-2}·s^{-1}, similar to 'Allstar', 'Chandler', 'Earlyglow', 'Evie 2', 'L'Amour', and 'Seascape', but higher than 'Darselect', 'Honeoye', or 'Jewel' with Trmmol ranging from 3.16 mmol·m^{-2}·s^{-1} to 3.98

$mmol \cdot m^{-2} \cdot s^{-1}$. Gas exchange measurements including Pn, g_s, and Trmmol were not affected by irrigation frequency.

Discussion

The ten cultivars tested in this study generally showed satisfactory vegetative growth in terms of PGI, leaf relative chlorophyll content, shoot and root dry weights, with five cultivars Allstar, Evie 2, Honeoye, L'Amour, and Seascape having visual scores of 3 or above. The earliest ripening cultivars in this study were June-bearing Honeoye and Earlyglow, producing ripe fruit 49.4 and 51.3 DAT, with corresponding cumulative GDDs of 536 and 556, respectively. The June-bearing 'Chandler' was the latest ripening cultivar, producing ripe fruit 65.7 DAT, with 783 GDDs.

Strawberry harvest season in midsouthern states including Arkansas, Louisiana, Mississippi, Oklahoma, and Texas, occurs from February to late May or early June, with peak production typically in April to May (Samtani et al., 2019). The first fruit harvest was in late April in this study, consistent with local strawberry harvest timing in an open field production system (Lewis, 2014). In this current study, the two earliest ripening June-bearing cultivars Earlyglow and Honeoye produced peak yield in April, all other tested cultivars produced peak yield in May. Identifying cultivars that produce earlier in the season can lead to higher profits for growers who can get their strawberries to market first. Combining those cultivars with a season extension tool such as a high tunnel could lead to sales many weeks before the competition can enter the market.

The ten cultivars generally produced lower yield and smaller fruit than reported ranges of approximately 450 to 500 g marketable fruit per plant (Anderson et al., 2019; Ballington et al., 2008; Gu et al., 2017; Yao et al., 2015). A possible reason might be the time of transplanting in spring using bare root liners. Local open field or high tunnel strawberry production systems in Mississippi typically use fall planting with plugs, which allows plants to establish vegetatively before flower and fruit production in spring (Husaini and Neri, 2016). Fall-planted strawberry cultivars required 1249.1 to 1374.3 GDDs from transplanting to first ripe fruit in a high tunnel production system in the same location (unpublished data), thus resulted in higher yield than spring planting. The two day-neutral cultivars 'Evie 2' and 'Seascape' produced the highest and second highest total yield of all tested cultivars, higher than all June-bearing cultivars. 'Evie 2' also produced yield of 56.8 g per plant in June when all June-bearing cultivars produce less than 2 g berry per plant, showing potential for season extension into months with warmer temperatures. Local daily average air temperatures during the first two weeks of June were between 22.2 °C and 29.2 °C, with daily maximum air temperature ranging from 30 °C to 33.9 °C. High temperatures are the major limiting factor of using day-neutral cultivars to extend harvest season in Mississippi, requiring heat tolerant cultivars.

Fall planting of strawberries during October to November in the south is limited by plant sources, with many nurseries starting plant deliveries in spring. This is likely due to the small production scale of strawberry and the low demand for strawberry plants in these states. The cultivars tested in this study are mostly not used in the southeastern states. However, 'Evie 2' exhibited potential to be used in strawberry production in the southeastern states given available transplants. By comparison, yields of the two earliest ripening cultivars Earlyglow and Honeoye were among the lowest of the ten tested cultivars. However, they may potentially be used in fall planting or in protected culture like high tunnels for off-season strawberry production.

Compared with the organic fertilizer, the conventional fertilizer increased plant growth index, leaf relative chlorophyll content, visual score, yield in May, daily water use, and net photosynthetic rate regardless of strawberry cultivars in this current study. This agreed with a previous study using the same two fertilizer types but in container grown southern highbush blueberry (*Vaccinium corymbosum* L.) cultivars, where the conventional fertilizer increased blueberry yield in 2016 (Li and Bi, 2019). The conventional fertilizer also tended to advance blueberry ripening for approximately one week compared to the organic fertilizer (Li and Bi, 2019), whereas the same two fertilizer types resulted in similar strawberry harvest date in this study. Nutrients in organic fertilizers are in organic forms and must go through mineralization for nutrients to be available to plant uptake (Lee, 2010; Roussos et al., 2017), resulting in a slow release of nutrient. Gaskell et al. (2009) reported it to be unpredictable to synchronize nitrogen (N) demand for establishing strawberry plants with release of N from various organic nutrient sources compared to conventional N sources. Large quantity and continuous application of organic fertilizers are required to achieve certain fertility and soil organic matter level for optimal yield in organic farming (Chang et al., 2010; Li et al., 2005). The two fertilizer types are applied in proportion to provide the same total amount of nutrients. Their effects on plant growth and fruit production are subject to the rate of nutrient release and the total amount of fertilizer available to plants. Their different effects on plant growth and crop yield may become more significant over time. Therefore, organic fertilization in container grown strawberry plant may require a supplement of liquid fertilizer to stimulate fast-acting effects.

The effect of irrigation frequency can vary among plant species with different water requirements or soilless growing substrates with varying physical and chemical properties (Li et al., 2018; Li et al., 2019a; Li et al., 2019b). Increasing irrigation frequency can improve growth and plant nutrient uptake by continually resupplying nutrient solution to the depletion zone around the roots. Silber et al. (2003) found that higher irrigation frequency led to more vegetative growth and higher concentrations of less mobile nutrients in iceberg lettuce (*Lactuca sativa* L.). *Rhododendron* species with low water requirement benefited from one irrigation per day over two irrigations: Encore azalea 'Chiffon' produced greater PGI, root biomass, and improved mineral nutrient uptake in roots under one irrigation per day (Li et al., 2018). Biomass production of *Hydrangea macrophylla* 'Merritt's Supreme' was not affected by irrigation frequency (Li et al., 2019b). In this current study, two irrigations per day increased substrate moisture, which may affect nutrient availability in the substrate and merits further investigation. Two irrigations per day also increased plant shoot dry weight when fertilized with the conventional fertilizer, but did not affect plant size, visual quality, gas exchange, strawberry yield, or fruit quality of the ten tested strawberry cultivars. This agreed with Silber et al. (2003) that higher irrigation frequency leads to increased vegetative growth, which can potentially be used in strawberry plant production to increase the number of runners per plant.

Soilless culture of strawberries is used in limited areas due to high production cost and high demands for management expertise. It is mostly used in greenhouses or high tunnels, where off-season strawberry production and high market demand can justify the production cost (Lieten, 2013). Planting strawberry plants in containers alleviates extensive soil management and the need for soil fumigation, and may potentially increase production sustainability. Containerized growth with drip irrigation makes strawberry plants less dependent on water supply, especially when bare-root liners were used, requiring greater amount of water than plugs during plant establishment (Hochmuth et al., 2006; Husaini and Neri, 2016). This study provides reference in fertilization and irrigation management in an alternative production system, which can be potentially used in strawberry plant nursery production or production of strawberry plants as edible ornamental plants. There might be potential of using container-grown strawberry plants in nursery production for propagation purposes or to be used in small-scale production for certain niche markets, which warrants further investigation.

Table 3.1 Vegetative growth of seven June-bearing ('Allstar', 'Chandler', 'Darselect', 'Earlyglow', 'Honeoye', 'Jewel', and 'L'Amour') and three day-neutral ('Evie 2', 'San Andreas', and 'Seascape') strawberry cultivars grown in Starkville, Mississippi in 2018.

Cultivar	PGI[z, y] (cm)	**Relative chlorophyll content**	Number of crowns (per plant)	Visual score (1-5)[x]	Shoot dry wt. (g per plant)	Root dry wt. (g per plant)
Allstar	41.2 ab	31.9 def	4.1 ab	3.0 bcde	71.4 a	13.5 abcd
Chandler	37.4 c	30.1 f	4.3 ab	2.9 bcde	65.8 a	10.1 d
Darselect	39.5 abc	31.0 ef	3.8 ab	2.6 e	65.1 a	14.6 abc
Earlyglow	38.3 bc	32.9 de	4.0 ab	2.8 cde	63.7 a	11.9 cd
Evie 2	37.0 c	36.3 ab	3.8 ab	3.0 bcde	58.8 a	9.6 d
Honeoye	40.9 ab	35.3 bc	4.2 ab	3.8 a	81.5 a	16.5 ab
Jewel	41.6 a	30.4 f	3.5 b	2.7 de	67.5 a	12.9 abcd
L'Amour	38.5 abc	33.5 cd	4.4 ab	3.2 bc	75.9 a	17.3 a
San Andreas	37.6 c	37.5 a	4.2 ab	2.9 cde	64.4 a	12.3 bcd
Seascape	38.7 abc	35.7 abc	5.2 a	3.3 b	63.2 a	11.5 cd
P-value	<.0001	<.0001	0.040	<.0001	0.13	<.0001

[z] Plant growth index (PGI) = [plant height + widest width 1 + width 2 (width at the perpendicular direction to width 1]/3.

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey's HSD test at $P \leq 0.05$.

[x] Plant visual quality was evaluated by a five-point scale, where 1= poor quality with severe leaf damage over 70%; 2= leaf damage of 50 to 70%, 3= moderate quality with 20 to 50% leaf damage; 4= good quality with minor leaf damage of less than 20%; 5=excellent quality without any leaf damage. A dead plant was rated 0 for the visual score.

Table 3.2 Effect of fertilizer type on plant growth index (PGI), leaf relative chlorophyll content, visual score, yield in May, daily water use, substrate moisture, and net photosynthetic rate (Pn) of container-grown strawberries grown in Starkville, Mississippi.

	PGI[y]	Relative chlorophyll content	Visual score	Yield in May	Daily water use (L per day)		Substrate moisture	Pn
Fertilizer[z]	(cm)		(1-5)	(g per plant)	19 June	26 June	(%)	(µmol m^{-2} s^{-1})
Organic	38.3 b	32.3 b	2.8 b	57.9 b	0.54 b	0.62 b	27.2 a	10.7 b
Conventional	39.9 a	34.6 a	3.2 a	67.9 a	0.65 a	0.73 a	24.6 b	12.0 a
P-value	0.0003	<.0001	<.0001	0.044	<.0001	0.0003	<.0001	0.0059

[z] Strawberry plants were fertilized with a conventional controlled release fertilizer or an organic fertilizer at comparable rates.

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey's HSD test at $P \leq 0.05$.

Table 3.3 Shoot dry weight affected by the interaction between irrigation frequency and fertilizer type and substrate moisture affected by the main effect of irrigation frequency of container-grown strawberries.

Irrigation frequency[z]	Fertilizer	Shoot dry wt. (g per plant)[y]	Substrate moisture (%)
Once	Organic	60.34 b	21.21 b
	Conventional	68.05 b	
Twice	Organic	60.71 b	30.55 a
	Conventional	81.82 a	
P-value		0.049	<.0001

[z] Seven June-bearing (‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’) and three day-neutral (‘Evie 2’, ‘San Andreas’, and ‘Seascape’) strawberry cultivars were grown in 2-gal containers irrigated once or twice per day with the same total irrigation volume, and fertilized with a conventional controlled release fertilizer or an organic fertilizer at comparable rates.

[y] Different lower-case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$.

Table 3.4 Fruiting characteristics including first harvest date, number of fruit per plant, berry size, soluble solids content, and fruit firmness of seven June-bearing (‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’) and three day-neutral (‘Evie 2’, ‘San Andreas’, and ‘Seascape’) strawberry cultivars grown in Starkville, Mississippi in 2018.

	First harvest date[z]	Number of fruit	Berry size	Soluble solids content	Fruit firmness
Cultivar	(DAT)	(per plant)	(g per berry)	(°Brix)	(N)
Allstar	58.6 bc	6.9 c	8.8 e	10.5 a	1.89 abc
Chandler	65.7 a	4.6 cd	11.7 d	10.4 a	1.32 e
Darselect	54.0 def	4.7 cd	14.0 bc	11.5 a	1.48 de
Earlyglow	51.3 fg	3.9 cd	9.3 e	11.5 a	1.49 de
Evie 2	60.9 b	16.5 a	14.8 b	8.4 c	1.53 de
Honeoye	49.4 g	4.4 cd	10.1 de	10.4 ab	1.60 cde
Jewel	58.4 bcd	6.0 cd	10.2 de	10.3 ab	1.73 bcd
L’Amour	57.3 bcde	3.1 d	12.2 cd	11.1 a	2.00 ab
San Andreas	53.7 efg	5.0 cd	17.8 a	8.7 bc	2.17 a
Seascape	54.4 cdef	12.3 b	14.2 bc	10.9 a	1.65 cd
P-value	<.0001	<.0001	<.0001	<.0001	<.0001

[z] Different lower-case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$.

Table 3.5 Monthly and total yield of seven June-bearing (‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’) and three day-neutral (‘Evie 2’, ‘San Andreas’, and ‘Seascape’) strawberry cultivars grown in Starkville, Mississippi in 2018.

	Strawberry yield in 2018 (g per plant)[z]			
Cultivar	April	May	June	Total
Allstar	5.0 c	52.0 cd	1.5 b	58.4 cd
Chandler	3.5 c	50.2 cde	1.9 b	55.7 cd
Darselect	18.6 ab	47.3 cde	0 b	65.8 cd
Earlyglow	17.9 ab	16.7 e	0.6 b	35.2 d
Evie 2	8.9 bc	170.6 a	56.8 a	236.3 a
Honeoye	24.4 a	16.6 e	0.5 b	41.5 d
Jewel	4.6 c	53.8 cd	0 b	58.5 cd
L’Amour	10.0 bc	25.3 de	0.5 b	35.8 d
San Andreas	23.4 a	61.1 c	5.3 b	89.8 c
Seascape	22.5 a	135.7 b	9.4 b	167.6 b
P-value	<.0001	<.0001	<.0001	<.0001

[z] Different lower-case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$.

Table 3.6 Daily water use measured on two dates and substrate moisture measured on 27 June 2018 of seven June-bearing (‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’) and three day-neutral (‘Evie 2’, ‘San Andreas’, and ‘Seascape’) strawberry cultivars grown in containers in Starkville, Mississippi.

	Daily water use (L per day)[z]		Substrate moisture (%)
Cultivar	19 June	26 June	27 June
Allstar	0.67 ab	0.78 a	28.0 a
Chandler	0.58 abc	0.73 a	25.0 ab
Darselect	0.60 abc	0.66 a	23.1 b
Earlyglow	0.58 abc	0.67 a	26.8 ab
Evie 2	0.53 bc	0.65 a	26.9 ab
Honeoye	0.65 abc	0.72 a	27.5 a
Jewel	0.57 abc	0.62 a	27.3 ab
L’Amour	0.71 a	0.72 a	23.8 ab
San Andreas	0.54 bc	0.61 a	25.5 ab
Seascape	0.53 c	0.57 a	25.0 ab
P-value	0.0004	0.074	0.0037

[z] Different lower-case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$.

Table 3.7 Gas exchange measurements including net photosynthetic rate (Pn), stomatal conductance (g_s), and transpiration rate (Trmmol) of seven June-bearing (‘Allstar’, ‘Chandler’, ‘Darselect’, ‘Earlyglow’, ‘Honeoye’, ‘Jewel’, and ‘L’Amour’) and three day-neutral (‘Evie 2’, ‘San Andreas’, and ‘Seascape’) strawberry cultivars grown in containers in Starkville, Mississippi.

Cultivar	Pn (μmol m^{-2} s^{-1})^{z}	g_s (mol m^{-2} s^{-1})	Trmmol (mmol m^{-2} s^{-1})
Allstar	9.8 d	0.10 a	4.37 ab
Chandler	11.2 bcd	0.12 a	4.73 ab
Darselect	10.3 bcd	0.072 a	3.16 b
Earlyglow	10.7 bcd	0.11 a	5.57 ab
Evie 2	11.2 bcd	0.11 a	4.61 ab
Honeoye	9.7 d	0.089 a	3.74 b
Jewel	9.9 cd	0.083 a	3.98 b
L’Amour	14.4 a	0.14 a	5.53 ab
San Andreas	13.4 ab	0.14 a	6.65 a
Seascape	13.0 abc	0.12 a	5.09 ab
P-value	<.0001	0.026	0.0006

[z] Different lower-case letters within a column suggest significant difference indicated by Tukey’s HSD test at $P \leq 0.05$.

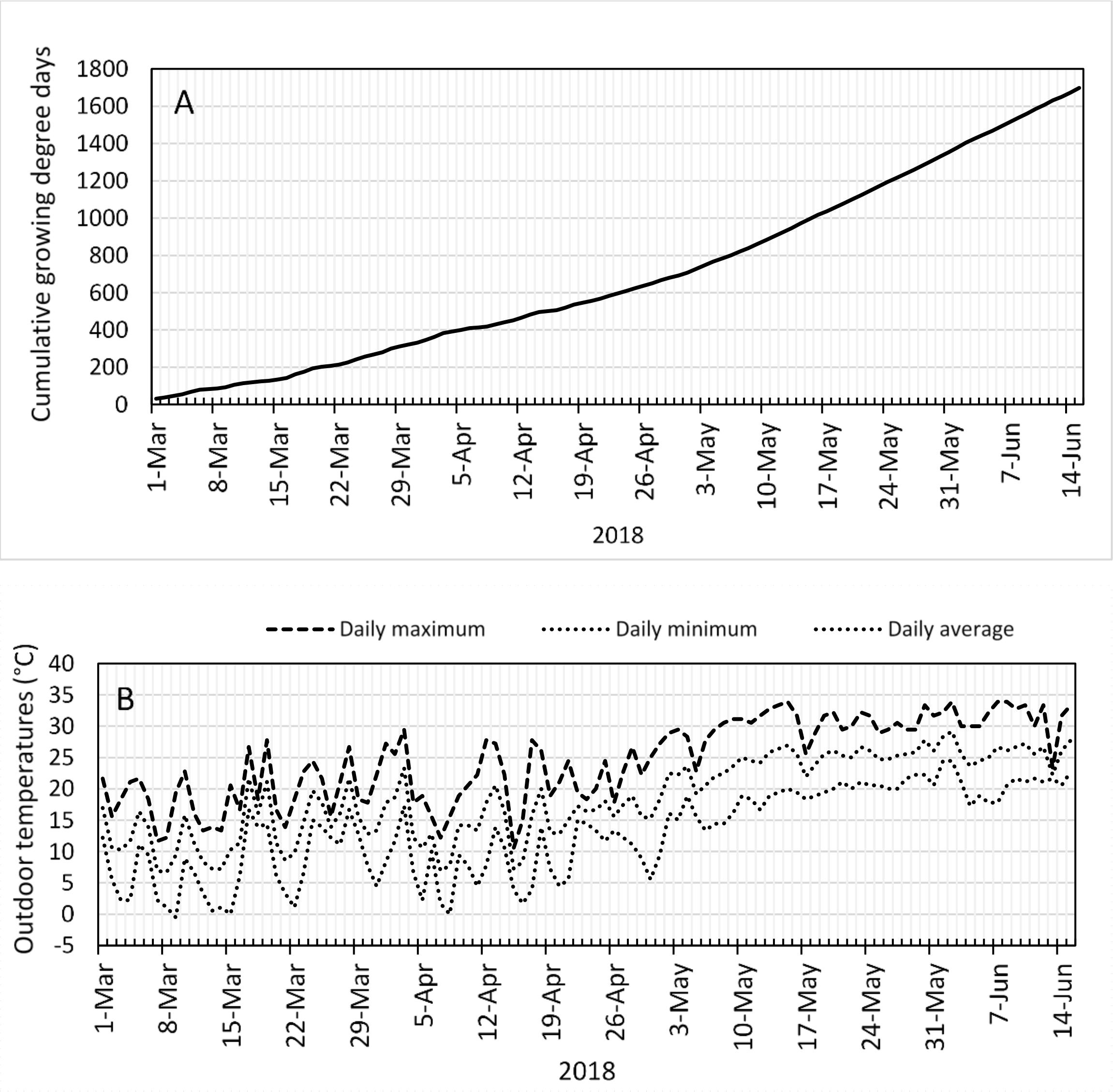

Figure 3.1 Accumulative growing degree days (GDDs) (A) and outdoor daily air temperatures (B) from 1 Mar. to 15 June 2018 in Starkville, Mississippi.

GDDs = $(T_{\text{daily max}} + T_{\text{daily min}})/2 - T_{\text{base}}$. T_{base} = 3 °C for strawberries. GDDs were calculated on a daily basis, and cumulative GDDs during certain time periods were estimated by summing up daily GDDs; Local outdoor air temperature data was obtained from the USDA Natural Resources Conservation Service website.

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CHAPTER IV

CONCLUSIONS

Cultivar was an important factor in the production of strawberry in a high tunnel or the container production system. Of the thirteen variables examined in the high tunnel study, ten variables including yield and total phenolic content, had significant differences due to cultivar alone and the other three variable including fruit firmness, titratable acidity, and total unmarketable yield had significant differences due to the interaction of cultivar and mulch color. Similarly, in the outside container study, all but two of the measured variables (shoot dry weight and water use 26 June) had significant differences due to cultivar.

In the 2017 to 2018 growing season, ‘Camino Real’, ‘Chandler’, and ‘Strawberry Festival’ produced the comparable highest total marketable yields of 482.9 g to 559.4 g per plant, with ‘Sensation’ producing the lowest total marketable yield of 215.8 g per plant due to plant loss in establishment. It is useful to identify cultivars that can thrive in local climates different than the places where the cultivars were first developed. Multiple season cultivar comparisons would further help Mississippi growers choose cultivars that would maximize their profits.

It is clear that high tunnels can be useful tools for crop protection, mitigating conditions such as excessive rainfall and frost events. However, the potential for extending the growing season is the real reason a grower should consider investing in a tunnel. Compared to the local outdoor environment, the high tunnel used in this study increased daily minimum, average, and maximum air temperatures and reduced the likelihood of frost incidence. In addition, fruit harvest was advanced by 4 to 6 weeks compared to typical local strawberry harvest in open field production.

This study showed a limited influence of mulch color on the variables examined. Compared to the black plastic mulch, red mulch decreased marketable yield in March, but increased marketable yield in May. This may be due to the two colors different effects on soil temperature. This aspect of the mulch was not examined in this study but it would be something to look at in future research. Mulch type did not affect vegetative growth of strawberry plants, or strawberry quality variables including single berry weight, SSC, TPC, or TAC.

Of the ten tested cultivars in the outdoor container study, the two day-neutral cultivars Evie 2 and Seascape produced higher total and late-season yields than any other June-bearing cultivar. It is possible that the day neutral cultivars were better able to handle the higher temperatures that began in May. ‘Honeoye’ was the earliest ripening cultivar, significantly earlier than the common commercial standard ‘Chandler’. Early ripening could prove to be beneficial for Mississippi growers in other contexts. The conventional fertilizer increased plant vegetative growth, May yield, and net photosynthesis of strawberry plants compared to the organic fertilizer at comparable rates, but did not affect time of fruit production or fruit quality. This suggests organically fertilized strawberry plants grown in soilless substrate would require a combination of granular and liquid fertilizer sources to satisfy plant nutrient requirements effectively. It also might suggest that bacterial amendments may be applied to aid in the mineralization of organic fertilizers. Substrate moisture was the only variable where organic fertilizer produced significantly higher averages than conventional fertilizer. This, combined with the higher daily water use for conventional fertilizer, would suggest conventionally fertilized plants were able to utilize the applied irrigation more efficiently. More frequent irrigation in combination with the conventional fertilizer was beneficial for plant vegetative growth with improved shoot dry weight.