

Strawberry Cultivar Evaluation for Fall-planted High Tunnel System

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KEYWORDS. day-neutral, *Fragaria ×ananassa*, north-central US, quality, short-day, yield

ABSTRACT. Locally produced strawberries (*Fragaria ×ananassa*) have outstanding market potential. But strawberry production has been decreasing in the north-central United States, partly because of high production risks associated with the traditional matted-row system. The annual plasticulture system attracts attention but its low yield limits the wide adoption of the production system in the north-central United States. High tunnels are widely used to extend strawberry seasons worldwide, but the system was not fully explored in the United States. Although the benefits of growing strawberries in high tunnels were recognized, information on suitable strawberry cultivars specific for the fall-planted high tunnel production system is limited. A wide range of short-day and day-neutral strawberry cultivars, including recently released cultivars, were evaluated in the fall-planted annual plasticulture high tunnel systems for three seasons. Averaged among cultivars, the marketable yields were 1.96, 1.35, and 2.27 lb/plant for 2015–16, 2019–20, and 2020–21 seasons, respectively. The combined use of high tunnels and floating rowcovers created favorable microclimate conditions that led to high yields. Florida Radiance, San Andreas, Chandler, and Rocco were the top-yielding cultivars. Besides Chandler, the other top-yielding cultivars entered peak harvest in the second half of April. Harvests ended at the end of May or early June. All cultivars reached the US Department of Agriculture standard for total soluble solids in all three seasons, although Camino Real, FL Radiance, and Sweet Sensation consistently had relatively lower sugar content. Considering a warm-season crop could grow in high tunnels before or after strawberry, a diversified cropping system involving strawberry and other vegetables is highly valuable for high tunnel production systems in the north-central United States. This study did not compare cultivars' resistance to diseases, but it should be a critical factor in selecting cultivars. Future studies are also warranted to evaluate the effects of incorporating soil treatments and cover cropping for suppressing diseases in the soil-based high tunnel system. Sustainable management strategies to control two-spotted spider mites (*Tetranychus urticae*) are also crucial in successfully using the system in the north-central United States.

Locally produced small fruit including strawberry (*Fragaria ×ananassa*), highbush blueberry (*Vaccinium corymbosum*), blackberry (*Rubus* sp.), and raspberry (*Rubus idaeus*) are in exceptionally high demand (Wolff 2021). A close to \$30 million market is created by strawberry produced and sold exclusively at the local fresh market in North Carolina (Gu et al. 2017). The COVID-19 pandemic revealed the vulnerability of the centralized food system and further increased awareness of local food production (Campbell 2021).

Strawberry is traditionally grown in the matted-row system in the north-central regions of the United States (Hokanson and Finn 2000). Bare root strawberry plants of short-day cultivars are set in the spring in bare soil. Runners develop throughout the summer to fill in

the beds. Fruit is first harvested in the second year and the planting is renovated annually. Plantings are usually maintained for two to three seasons (Ellis et al. 2006). Weed control is one of the major challenges in the production system; high production risks related to extreme weather

conditions such as late frost, excessive precipitation, and drought also pose challenges. Strawberry production decreased in most states in the north-central United States in the past decades. In Indiana alone, strawberry farms decreased from 233 to 199 farms between 2007 and 2017, and production acreage decreased from 415 to 254 acres [US Department of Agriculture (USDA) 2012, 2017].

The annual plasticulture system successfully used in the southern United States has attracted farmers' attention in the north-central region. In this system, short-day strawberry plugs are transplanted in plastic-covered beds in late summer or fall. Fruits are harvested in spring the following year and after the fruiting season plants are removed. The annual plasticulture system largely reduces the burden of weed control and facilitates harvest a few months after planting (Poling 1993); however, low yields limit the wide adoption of the annual plasticulture systems in cooler climates (Demchak et al. 2005; Guan 2017).

High tunnels provide an opportunity for annual plasticulture strawberry production in the north-central United States. High tunnels are unheated, plastic-covered structures that provide intermediate environmental protection and controls. This structure protects plants from strong winds and rainfall and provides additional heat units and moderate frost protection (Carey et al. 2009). A national USDA initiative administered through the Natural Resources Conservation Service (NRCS), Environmental Quality Incentives Program has facilitated a dramatic increase in high tunnel construction. More than 400 high tunnels were funded between 2012 and 2020 in Indiana alone, not including those constructed without the assistance of NRCS. As more high tun-

Units			
To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
0.3048	ft	m	3.2808
2.54	inch(es)	cm	0.3937
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
1.1209	lb/acre	kg·ha ⁻¹	0.8922
0.0254	mil(s)	mm	39.3701
28.3495	oz	g	0.0353
33.9057	oz/yd ²	g·m ⁻²	0.0295
(°F - 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

Table 1. Strawberry cultivar names, types, and the seasons that the cultivars were evaluated in high tunnels at the Southwest Purdue Agriculture Center, Vincennes, IN, USA in 2015–16, 2019–20, and 2020–21 seasons.

Cultivar	Origin ⁱ	2015–16	2019–20	2020–21
Short-day cultivars				
Benicia	California	X ⁱⁱ		
Camarosa	California	X	X	
Camino Real	California	X	X	X
Chandler	California	X	X	X
Fronteras	California		X	
Ruby June	California		X	X
Florida Radiance	Florida	X	X	X
Strawberry Festival	Florida	X		
Sweet Charlie	Florida	X		
Sweet Sensation (Florida Sensation)	Florida		X	X
Flavorfest	Maryland			X
Galletta	North Carolina			X
Liz	North Carolina		X	X
Rocco	North Carolina			X
Day-neutral cultivars				
Albion	California	X		
San Andreas	California	X	X	X
Sweet Ann	California	X		
Florida Beauty	Florida		X	

ⁱ U.S. state where cultivar was bred.ⁱⁱ X indicates the cultivar was evaluated in the production season.

nels are built in the region, there is an increasing need to diversify crop production and increase the system's sustainability both economically and productively.

High tunnels are widely adapted for strawberry production worldwide (Van Delm et al. 2016; Zhang et al. 2017). In China, ~90% of strawberry acreage is in protected cultures

including greenhouses, high tunnels, and low tunnels (Zhang et al. 2017). Short-day cultivars are planted for winter and spring production and day-neutral cultivars are used to produce fruit in summer and fall.

Opportunities for growing strawberry in high tunnels have been evaluated in the United States. Previous studies found high tunnel production systems reduced the production risk associated with extreme weather conditions, increased fruit quality, and extended overall harvest duration compared with open-field production (Gu et al. 2017; Gude et al. 2018; Kadir and Carey 2004; Kadir et al. 2006; Rowley et al. 2010, 2011; Wallace and Webb 2013). Gude et al. (2018) and Rowley et al. (2011) evaluated summer and fall harvests for spring-planted day-neutral cultivars in Kansas and Utah. The production system is limited by high temperatures in the summer. Economic analysis suggested the system is marginally profitable (Rowley et al. 2011). Other studies evaluated fall-planted cultivars. The harvest windows for fall-planted short-day strawberries were 4 to 6 weeks earlier compared with open-field production in studies conducted in Utah (Rowley et al. 2010) and Kansas (Kadir et al. 2006), and 6 to 8 weeks longer in Texas (Wallace and Webb 2013).

Strawberry has a great potential to be incorporated as a rotational crop in high tunnels.

In the fall-planted system, the production season (fall, winter, and spring), in general, does not overlap with traditional high tunnel crops including tomato (*Solanum lycopersicum*) and cucumber (*Cucumis sativus*) for example. These high-value crops can be grown in the structure following strawberry. Alternatively, cover cropping or implementing soil disinfection strategies can be conducted in the summer, which is likely more effective and efficient in enhancing soil fertility and reducing disease pressures when performed in the summer rather than in the fall or spring.

The benefits of high tunnel production system are recognized, but information on suitable strawberry cultivars is limited. Strawberry cultivars have undergone tremendous changes in the past few decades. More than 100 cultivars were introduced to the market from the 1980s to early 2000 (Faedi et al. 2002). Multiple new cultivars including Flavorfest (Lewers et al. 2017), Florida Beauty (Whitaker et al. 2017), Liz and Rocco (Fernandez et al. 2020), and Fronteras (Larson and Shaw 2016) were released in the past 5 years. Performance of strawberry cultivars exhibits strong genotype by environment interactions, which indicates breeding

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and cultivar selection need to target regionally climatic conditions and production systems (Hokanson and Finn 2000).

High tunnel studies conducted in Utah and Kansas focused on cultivars Chandler and Sweet Charlie (Kadir et al. 2006; Rowley et al. 2010), the most widely grown plasticulture cultivars in the southern United States (Poling et al. 2005). A study conducted in North Carolina in an organically managed high tunnel system evaluated additional short-day and day-neutral cultivars and identified Florida Radiance, Benicia, and Camino Real as promising cultivars for the in-ground high tunnel production system. However, low sugar content and small fruit size of most cultivars during peak harvest raised concerns (Gu et al. 2017).

In the current study, we compared yields, harvest durations, and fruit quality of 18 strawberry cultivars in fall-planted high tunnel production systems in Indiana for three seasons. The study provides farmers with readily available information on evaluating the feasibility of the production system and provides guidance for cultivar selection.

Materials and methods

PLANTING AND HIGH TUNNEL MANAGEMENT. The experiment was conducted in gothic-style high tunnels (Rimol Greenhouse Systems, Hooksett, NH, USA) at the Southwest Purdue Agricultural Center located in Vincennes, IN, in 2015–16, 2019–20, and 2020–21 seasons. The high tunnels are 30 ft wide and 96 ft long, with 6-ft-high side walls and 15-ft-high centers. Soil type is a fine sandy loam with 0.9% organic matter. Before strawberry, the high tunnels were planted with tomato in the 2015–16 season and cowpea (*Vigna unguiculata*) before the 2019–20 and 2020–21 seasons. Six beds were made inside the high tunnels, which measured 20 inches wide and 3 inches high with 4-ft center-to-center bed spacing. The beds were covered with 3-ft-wide and 1-mil-thick black plastic mulch (Trickle-EEZ Irrigation Inc., St. Joseph, MI, USA). One drip tape with 8-inch emitter spacing was placed in the middle of each bed. Row middles were covered with a 3.2-oz/yard² woven white groundcover (Dewitt Co., Sikeston, MO, USA) on the top and 1-oz/yard² black weed barrier (Dewitt Co.) on the bottom.

Ten strawberry cultivars were evaluated in each of the three seasons. We selected cultivars based on market availability and performance in previous seasons' evaluations. Cultivar names, types, origins, and evaluation seasons are presented in Table 1. Plug plants (McNitt Growers, Carbondale, IL, USA) were planted in two rows staggered 10 inches apart on each bed; in-row spacing was 14 inches. Plugs were planted on 27 Aug, 6 Sep, and 28 Aug in 2015–16, 2019–20, and 2020–21 seasons, respectively. A randomized complete block design was used in each of the three seasons. In the 2015–16 season, the experiment had three blocks and 22 plants per cultivar per block. In the 2019–20 and 2020–21 seasons the experiment had six blocks and eight plants per cultivar per block.

The high tunnels were equipped with roll-up sidewalls that automatically

opened when temperatures were above 70 °F in the fall, and 80 °F in the winter. During the blooming periods in spring, sidewalls were opened or partially opened when temperatures were above 55 °F to encourage wind flow. Floating rowcovers with 1.5 oz/yard² thickness and 50% light transmission (Row Cover Supreme; Greenhouse Megastore, Danville, IL, USA) were used in winter and spring. Rowcovers were supported by wire hoops that were 18 inches above the ground in the center and placed 5 ft apart. In the 2015–16 season, rowcovers were applied at nights when the outdoor temperatures were expected to be lower than 35 °F and taken off during days when temperatures inside the high tunnel were above 60 °F. In the 2019–20 and 2020–21 seasons, floating rowcovers were used in spring for frost protection as described previously, and in fall and winter, floating rowcovers were

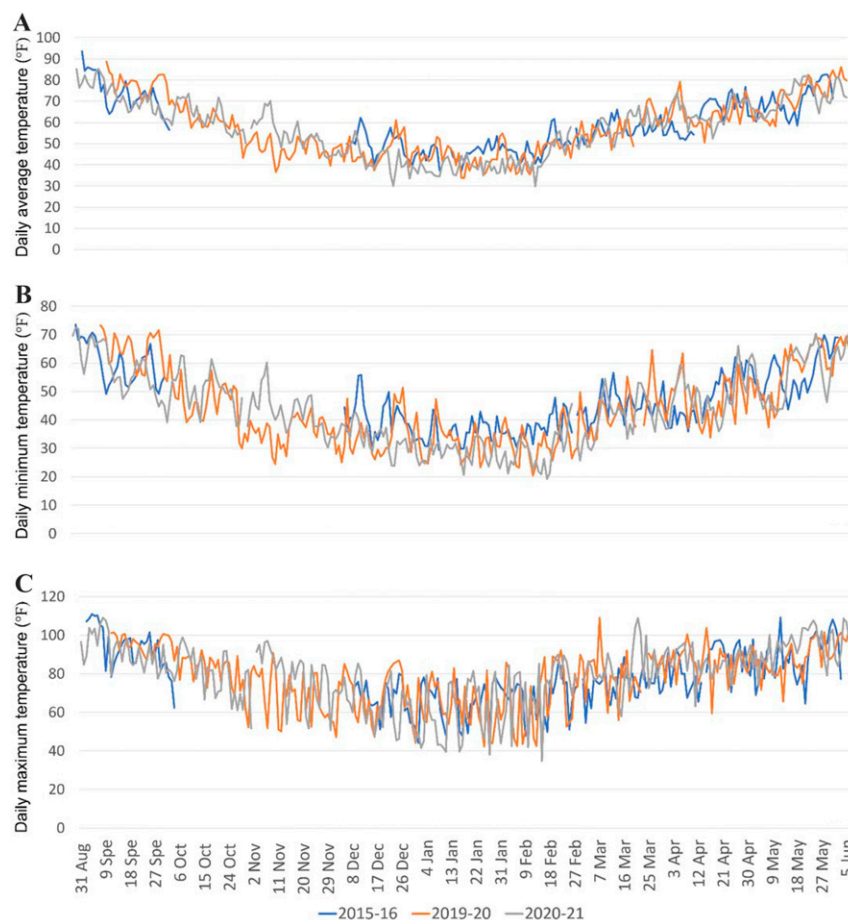


Fig. 1. Daily average (A), minimum (B), and maximum (C) temperatures measured at plant canopies during 2015–16, 2019–20, and 2020–21 strawberry seasons in high tunnels at the Southwest Purdue Agriculture Center, Vincennes, IN, USA. Data between 5 Oct and 7 Dec 2015 were missing because of data logger malfunction; $(^{\circ}\text{F} - 32) \div 1.8 = ^{\circ}\text{C}$.

used when expected outdoor temperatures were below 25 °F, resulting in less frequent use of floating rowcovers compared with the 2015–16 season. Air temperatures around the plant canopy were recorded with data loggers (Pro V2; Onset Computer Corp., Bourne, MA, USA). The daily average, minimum, and maximum temperatures in the three seasons are shown in Fig. 1.

FERTILITY AND PEST MANAGEMENT. Fertilizers were applied based on soil test recommendations (Standard test packages; A&L Great Lakes Laboratory, Fort Wayne, IN, USA). In the 2015–16 season, granular fertilizers at a rate of 60 lb/acre nitrogen (N) from 46N–0P–0K (Shaw’s Turf Food; Knox Fertilizer Co., Knox, IN, USA), 1 lb/acre boron from boron 15% (Winfield Solutions LLC, St. Paul, MN, USA), and 2 lb/acre zinc from zinc sulfate (0N–0P–0K–17.5S–35.5Zn; Winfield Solutions LLC) were incorporated when beds were formed. Fertigation was used in spring. On average, 0.5 lb/acre N per day was applied from the end of February to the middle of May using potassium nitrate and urea ammonium nitrate 28%. A total of 105 lb/acre N was applied in the 2015–16 season. No granular fertilizers were incorporated in soils in the 2019–20 and 2020–21 seasons. Plants were fertigated with 4N–0P–6.6K complete fertilizer (Brandt Consolidated, Inc., Springfield, IL, USA) in fall and potassium nitrate [13.7N–0P–38.5K (Krista K; Yara Intl., Oslo, Norway)] in spring. A total of 60 lb/acre N was applied in each fall and spring.

Yellowstriped armyworm (*Spodoptera ornithogalli*) caused damage to the leaves and crowns of newly planted strawberry plants in all three seasons. We managed the pest through one to two applications of *Bacillus thuringiensis* ssp. *aizawai* (Agree WG; Certis USA LLC, Columbia, MD, USA). Powdery mildew (*Podosphaera aphanis* var. *aphanis*) was encountered in Fall 2015. It was controlled with one application of cyflufenamid (Torino; Gowan Co. LLC, Yuma, AZ, USA) followed by one application of quinoxifen (Quintec, Gowan Co. LLC). Gray mold (*Botrytis cinerea*) caused damage to the fruit in all three seasons. Captan (Captan 50WP; Albac Inc., Ankeny, IA, USA) was sprayed once in Spring 2016 to manage this disease. Two-spotted spider

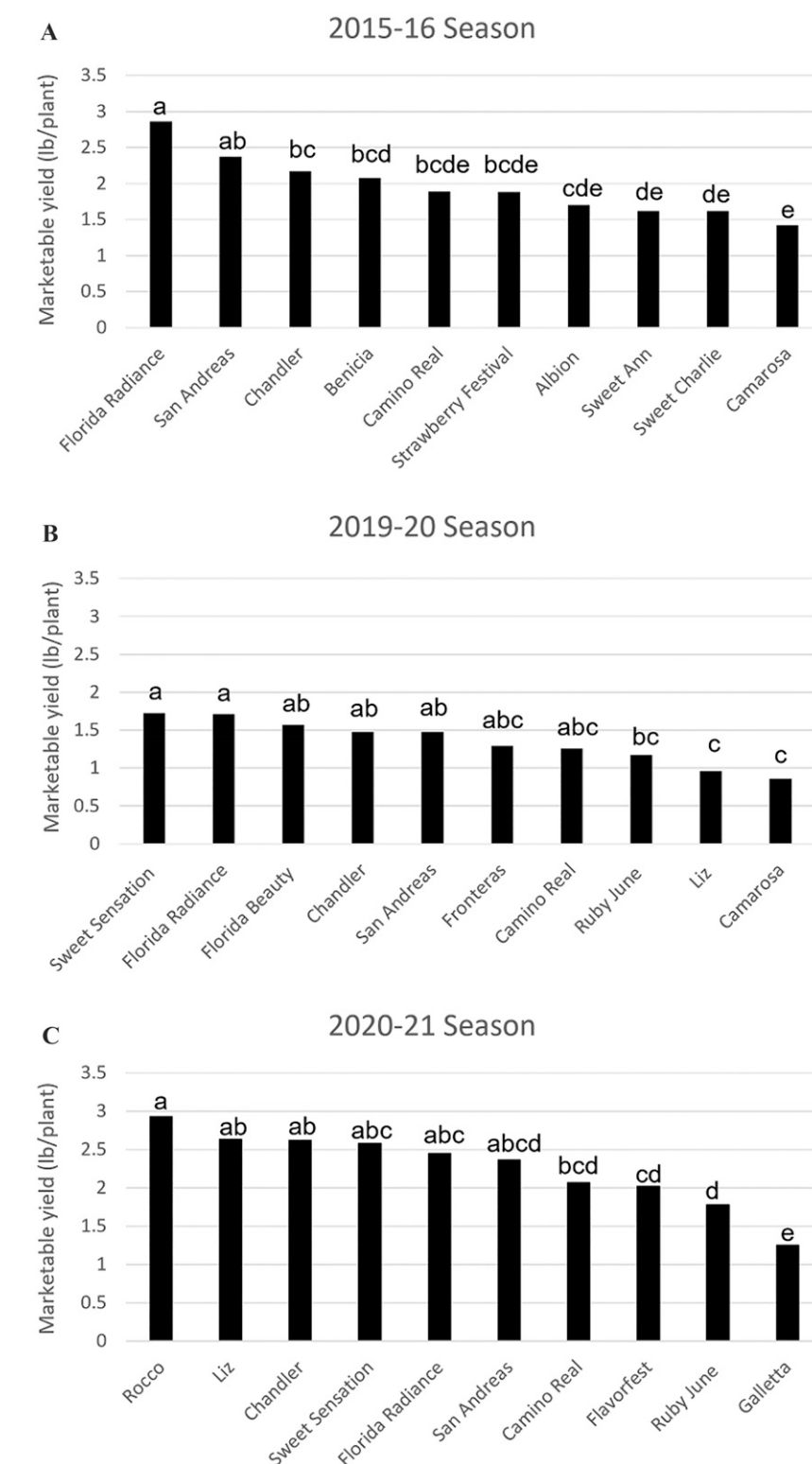


Fig. 2. Marketable yield of fall-planted strawberry cultivars in high tunnels in 2015–16 (A), 2019–20 (B), and 2020–21 (C) seasons at the Southwest Purdue Agriculture Center, Vincennes, IN, USA. Data were analyzed separately by year using analysis of variance. Means labeled by the same letters are not significantly different at $P \leq 0.05$ using Fisher’s protected least significant difference; 1 lb = 0.4536 kg.

mites (*Tetranychus urticae*) caused damage in all three seasons. Bifenazate (Acramite 50 WS; Chemtura Corp., Middlebury, CT, USA) was

used once in each of the three seasons as the label indicated. Potassium salts of fatty acids (M-Pede; Dow Agro Sciences, Indianapolis, IN, USA) were

applied as needed in the spring to provide additional control of two-spotted spider mites. Flonicamid (Beleaf 50 SG; FMC Corp., Philadelphia, PA, USA) was applied once to control potato aphids (*Macrosiphum euphorbiae*) in the early Spring 2021.

DATA COLLECTION AND STATISTICAL ANALYSES. The fully ripe strawberry fruit were harvested once per week in fall and twice per week in spring. Fruits were graded as marketable and nonmarketable (severely misshapen or damaged by diseases or insects); fruit weight and number per experimental plot were recorded. During peak harvest, five representative fruits of each experimental plot were selected to measure total soluble solids and firmness. A digital refractometer (Atago 3810; Cole-Parmer North America, Vernon Hills, IL, USA) was used to measure total soluble solids of juice extracted from each fruit. A handheld penetrometer (FDK32 Force Dial; Wagner Instruments, Greenwich, CT, USA) with a 7-mm tip was used to measure flesh firmness at the shoulder of each fruit. Data were analyzed separately by year by analysis of variance using statistical software (JMP Pro 16; SAS Institute Inc., Cary, NC, USA). Differences among means were tested by Fisher's protected least significant difference at $\alpha = 0.05$.

Results and discussion

YIELD. Marketable yields ranged from 1.42 to 2.86 lb/plant in the 2015–16 season, 0.86 to 1.72 lb/plant in 2019–20 season, and 1.25 to 2.93 lb/plant in 2020–21 season (Fig. 2). Averaged among cultivars, the marketable yields were 1.96, 1.35, and 2.27 lb/plant for 2015–16, 2019–20, 2020–21 seasons, respectively. Yields in the 2019–20 season were severely affected by two-spotted spider mites despite miticides being applied to control the pest. Unmarketable fruit accounted for $\approx 10\%$ of the total yields and was primarily due to misshapen fruit at the beginning of spring harvest in all three seasons (data not shown).

Using similar production systems, 'Chandler' yielded 1.66 lb/plant when planted on 4 Sep in North Logan, UT, USA (Rowley et al. 2010). The average yield of 10 cultivars was 0.8 lb/plant in an organically managed high tunnel in North Carolina (Gu et al. 2017). In

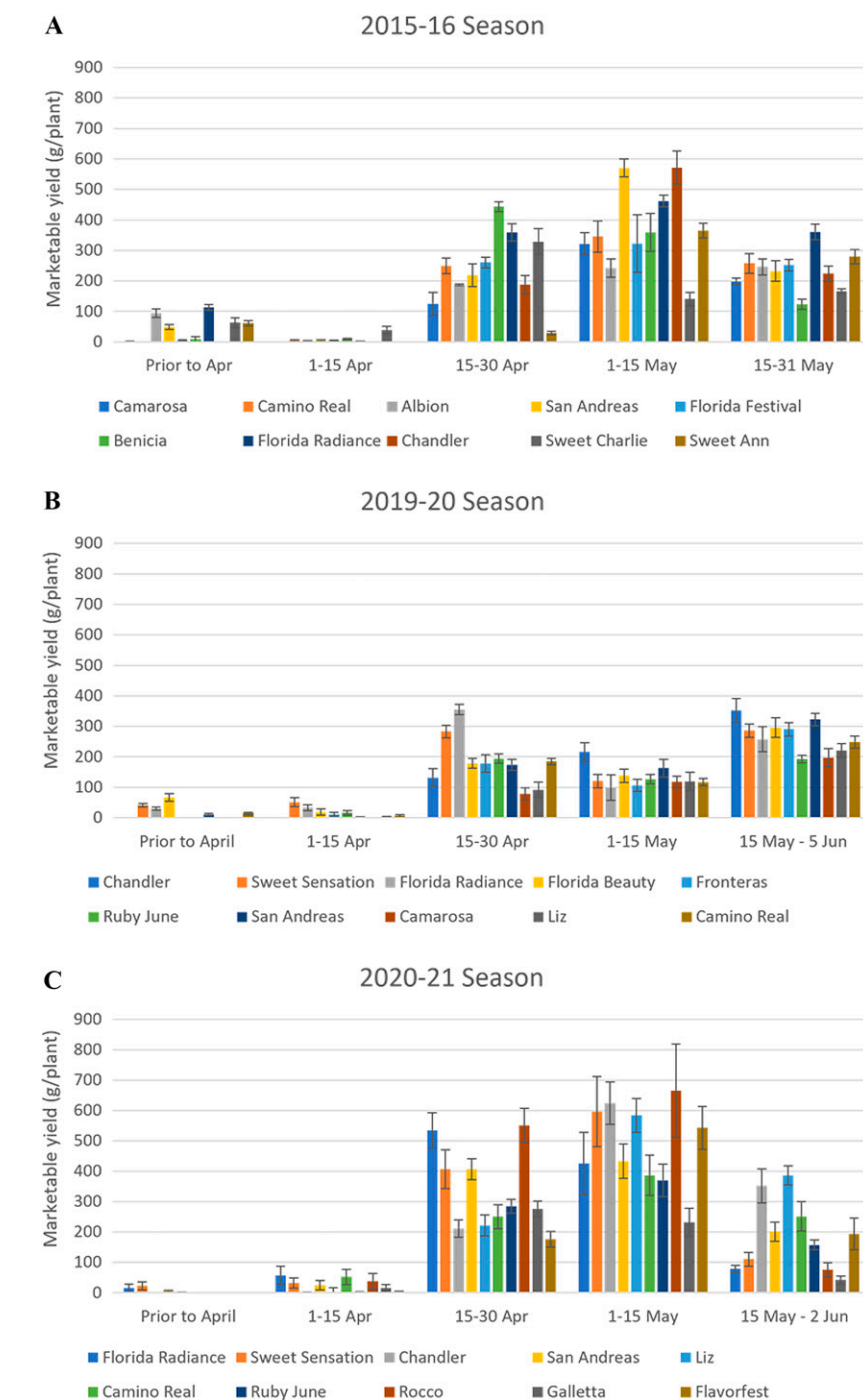


Fig. 3. Harvest period of fall-planted strawberry cultivars grown in high tunnels in 2015–16 (A), 2019–20 (B), and 2020–21 (C) seasons at the Southwest Purdue Agriculture Center, Vincennes, IN, USA. Data were analyzed separately by year using analysis of variance. Vertical lines through data points are standard error of the yield of each cultivar at the harvest period; 1 g = 0.0353 oz.

Mississippi, the yield of four cultivars ranged from 0.47 to 1.32 lb/plant when plugs were planted in November (Lalk et al. 2020). In Texas, yield was 1.4 lb/plant in September planting and 0.74 lb/plant in October planting (Wallace and Webb 2013). The yields of previous studies were equivalent to

or lower compared with the yields in the current study. Management practices and planting dates likely affected the yield potentials of the various cultivars.

Strawberry cultivars exhibited great differences in yields in the current production system. 'Florida Radiance', 'San

Andreas', 'Chandler', and 'Benicia' yielded more than 2 lb/plant in the 2015–16 season. 'Florida Radiance', 'San Andreas', and 'Chandler' were also evaluated in 2019–20 and 2020–21 seasons, and consistently had high yields. Among the top-yielding cultivars, Florida Radiance is a major cultivar for winter and early spring production in Florida since its release in 2008 from the University of Florida (Chandler et al. 2009). It has also been a major cultivar in protected culture in southwestern Spain for the past decade. Despite being categorized as a short-day cultivar, Florida Radiance develops more flowers under long-day conditions and requires less chilling for flower initiation than typical short-day cultivars (Whitaker et al. 2019). Florida Radiance was the top-yielding cultivar among 10 cultivars in North Carolina in an organically managed high tunnel system (Gu et al. 2017). It also demonstrated outstanding yield in the experiment conducted in Texas (Wallace and Webb 2013). The current study further demonstrated 'Florida Radiance' yields particularly well in the fall-planted high tunnel environments.

Chandler is the standard cultivar in open-field plasticulture production in the southeastern United States (Poling et al. 2005). In the fall-planted high tunnel system, 'Chandler' exhibited a high yield potential in the current study, as well as studies conducted in North Carolina (Gu et al. 2017), Kansas (Kadir et al. 2006), and Texas (Wallace and Webb 2013).

San Andreas had a significantly higher yield compared with the day-neutral cultivars Albion and Sweet Ann in the 2015–16 evaluation. The higher yield of 'San Andreas' than 'Albion' was reported previously (Shaw and Larson, 2009). 'Florida Beauty' had a similar yield as 'San Andreas' in the 2019–20 season. Although both Florida Beauty and San Andreas were marketed as day-neutral cultivars, they had equivalent or higher yields than most short-day cultivars in the high tunnel production system.

Cultivar Benicia was not included in the 2019–20 and 2020–21 seasons because of plant decline toward the end of harvest despite a high yield in the 2015–16 season. Plant decline of this cultivar was also reported in a previous study conducted in North Carolina (Gu et al. 2017). Although the factors causing this plant decline were not identified,

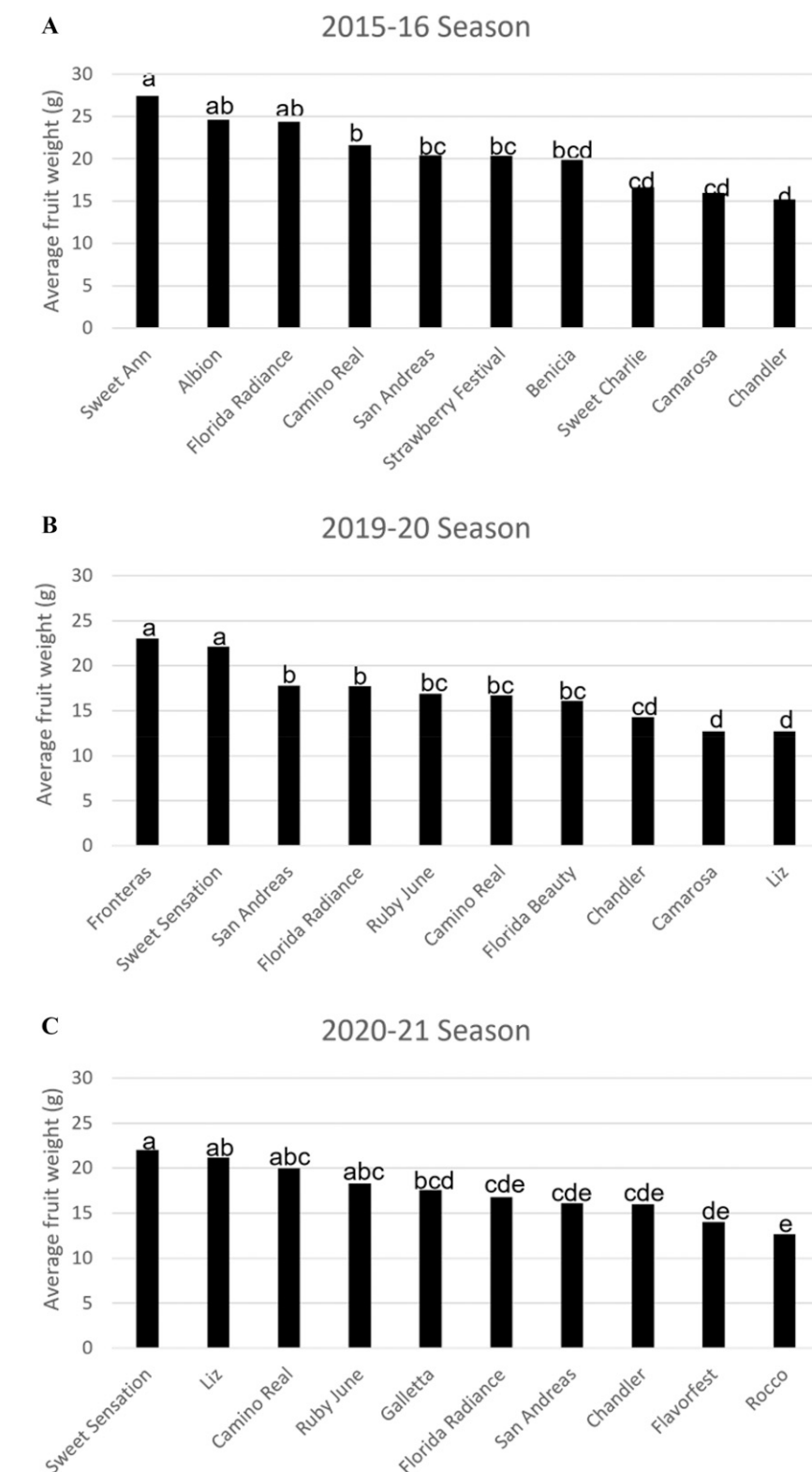


Fig. 4. Average fruit weight of fall-planted strawberry cultivars grown in high tunnels in 2015–16 (A), 2019–20 (B), and 2020–21 (C) seasons at the Southwest Purdue Agriculture Center, Vincennes, IN. Data were analyzed separately by year using analysis of variance. Means labeled by the same letters are not significantly different at $P \leq 0.05$ using Fisher's protected least significant difference; 1 g = 0.0353 oz.

'Benicia' is known to be extremely susceptible to *Verticillium* wilt [*Verticillium dahliae* (Shaw and Larson, 2012)].

In the 2020–21 season, the top-yielding cultivars were Rocco (2.93 lb/plant), Liz (2.63 lb/plant), Chandler

(2.62 lb/plant), Sweet Sensation (2.58 lb/plant), Florida Radiance (2.45 lb/plant), and San Andreas (2.36 lb/plant). Rocco and Liz are newly released short-day cultivars by North Carolina State University. ‘Liz’ was marketed with a consistently high yield (Fernandez et al. 2020); however, its yield was relatively low compared with other cultivars in the 2019–20 season. ‘Rocco’ showed an outstanding yield potential in the 2020–21 season; it also did well in an organically managed high tunnel in North Carolina (Fernandez et al. 2020). Additional evaluations are warranted to further demonstrate the yield potentials of the two recently released cultivars.

Fall-planted short-day cultivars are expected to yield more than 1 lb/plant to make the system economically viable (Demchak et al. 2005). The combined use of high tunnels and floating rowcovers created favorable microclimate conditions that led to yields being 1.35 to 2.27 times higher than the targeted yield in the current study. From the date of planting until the middle of November, the daily average temperatures stayed above 50 °F (Fig. 1). The favorable temperatures and short daylength encourage branch crown development and flower initiation. Average temperatures were between 30 and 50 °F in the winter, with minimum temperatures above 20 °F. Cultivars adapted to warmer climates with lower chilling requirements are likely to continue growing during this period and achieve high yields in the spring (Hancock 2020).

HARVEST PERIOD. Consistent across three seasons, the major spring harvest on early-ripening cultivars started in the second half of April (Fig. 3). Cultivars that had the highest spring early-season yield were Benicia, Florida Radiance, and Sweet Charlie in the 2015–16 season; Florida Radiance and Sweet Sensation in the 2019–20 season; Rocco, Florida Radiance, Sweet Sensation, and San Andreas in the 2020–21 season. Except for Sweet Charlie, which had a relatively lower yield than the other cultivars in the 2015–16 evaluation, most of the early-ripening cultivars were among the top-yielding cultivars.

Most cultivars had peak harvest in the first half of May, which declined in the second half of May in the 2015–16 and 2020–21 seasons. In the 2019–20 season, the yield was

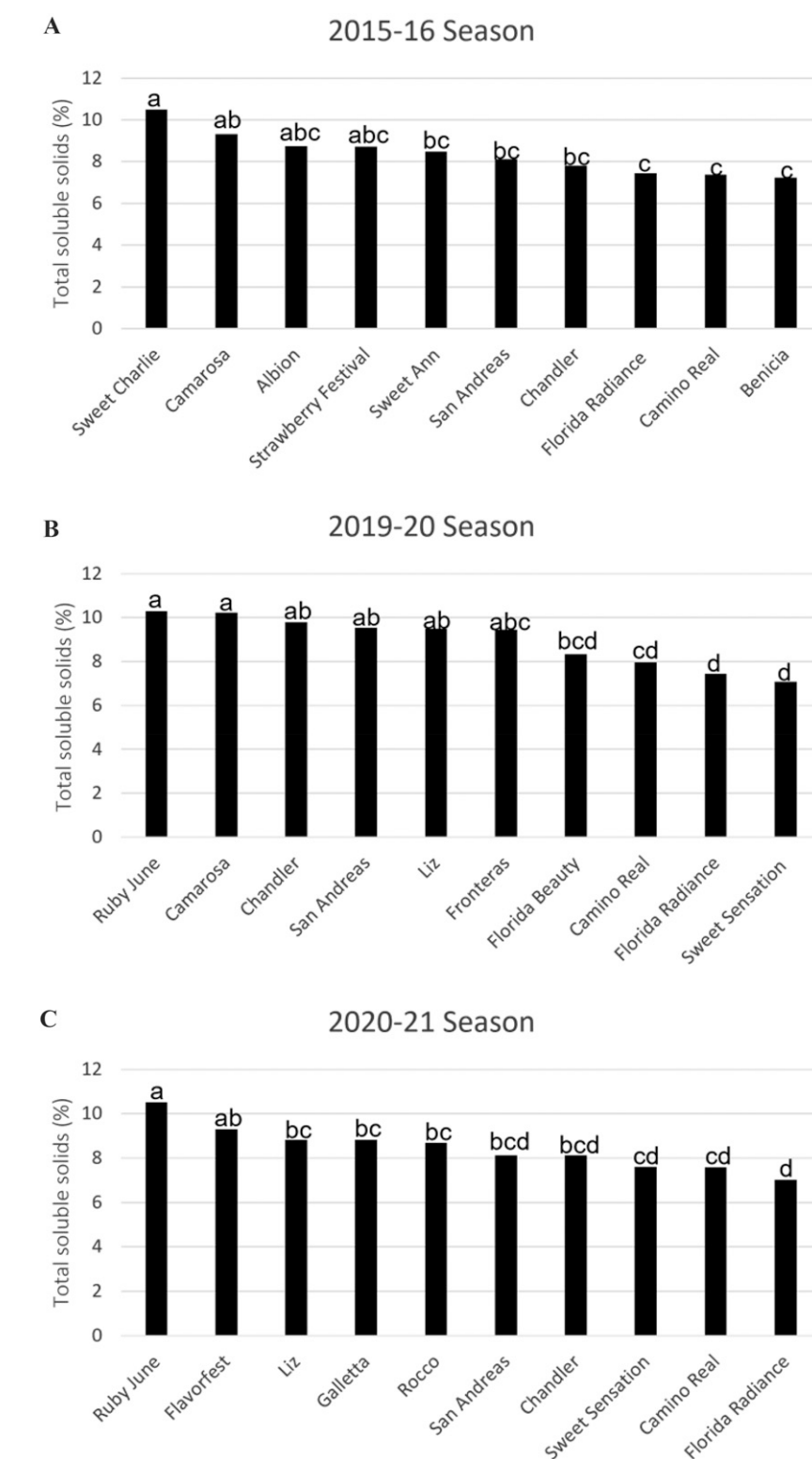


Fig. 5. Total soluble solids content of fall-planted strawberry cultivars grown in high tunnels in 2015–16 (A), 2019–20 (B), and 2020–21 (C) seasons at the Southwest Purdue Agriculture Center, Vincennes, IN, USA. Data were analyzed separately by year using analysis of variance. Means labeled by the same letters are not significantly different at $P \leq 0.05$ using Fisher’s protected least significant difference.

higher in the second half of May than early May. We ended harvest by the end of May or early June due to the

declined yield and high temperatures inside the high tunnels that negatively affected fruit quality (Fig. 1).

Day-neutral cultivars Albion, San Andreas, and Sweet Ann were evaluated in the 2015–16 season. The day-neutral cultivars had fruits ripen in the fall (harvested from October to December); however, the yield was much lower than in the spring harvest. In addition to the day-neutral cultivars bred in California, cultivars Florida Radiance, Sweet Charlie, Sweet Sensation, and Florida Beauty bred in Florida also had fruit ripen in the fall. Because of low yield and frequent frosts, fall and winter harvests were not feasible in the high tunnel systems in the north-central regions of the United States, which may be different from using a similar system in the US southern regions (Gu et al. 2017; Rana et al. 2020).

BERRY SIZE, SUGAR CONTENT, AND FIRMNESS. Average berry weight (total marketable fruit weight divided by marketable fruit number) varied greatly among cultivars (Fig. 4). ‘Sweet Ann’ (27 g) and ‘Fronteras’ (23 g) had the largest average berry weight in 2015–16 and 2019–20 seasons, respectively. ‘Sweet Sensation’ was among the largest-sized berries in both 2019–20 and 2020–21 seasons; average berry weight was ≈ 22 g. Consistent among three seasons, Chandler was among cultivars that had the smallest-size berries; its average berry weight was 14 to 16 g. ‘Rocco’ had the smallest berry size with an average berry weight of 13 g in the 2020–21 evaluation. ‘Camarosa’ also had relatively small-sized berries in the 2015–16 and 2019–20 seasons.

Strawberry flavors are a complex combination of sweetness, acidity, and aroma. Total soluble solids (TSS) is often used to express sweetness (Kleinhenz and Bumgarner 2013). US no. 1 grade strawberry fruit requires TSS of more than 7% (Mitcham 2014). The minimum TSS was reached by all the evaluated cultivars in all three seasons (Fig. 5). Comparing cultivars, Ruby June had the highest sugar content in both 2019–20 (10.3%) and 2020–21 (10.5%) seasons. The high sugar content of Ruby June was also observed in a study conducted in Virginia that compared TSS of strawberry cultivars Lucia, Ruby June, Scarlet, and Sweet Ann (Das and Samtani 2021). ‘Sweet Charlie’ had the highest TSS, 10.5% in the 2015–16 season. The same result was observed in the study comparing 10

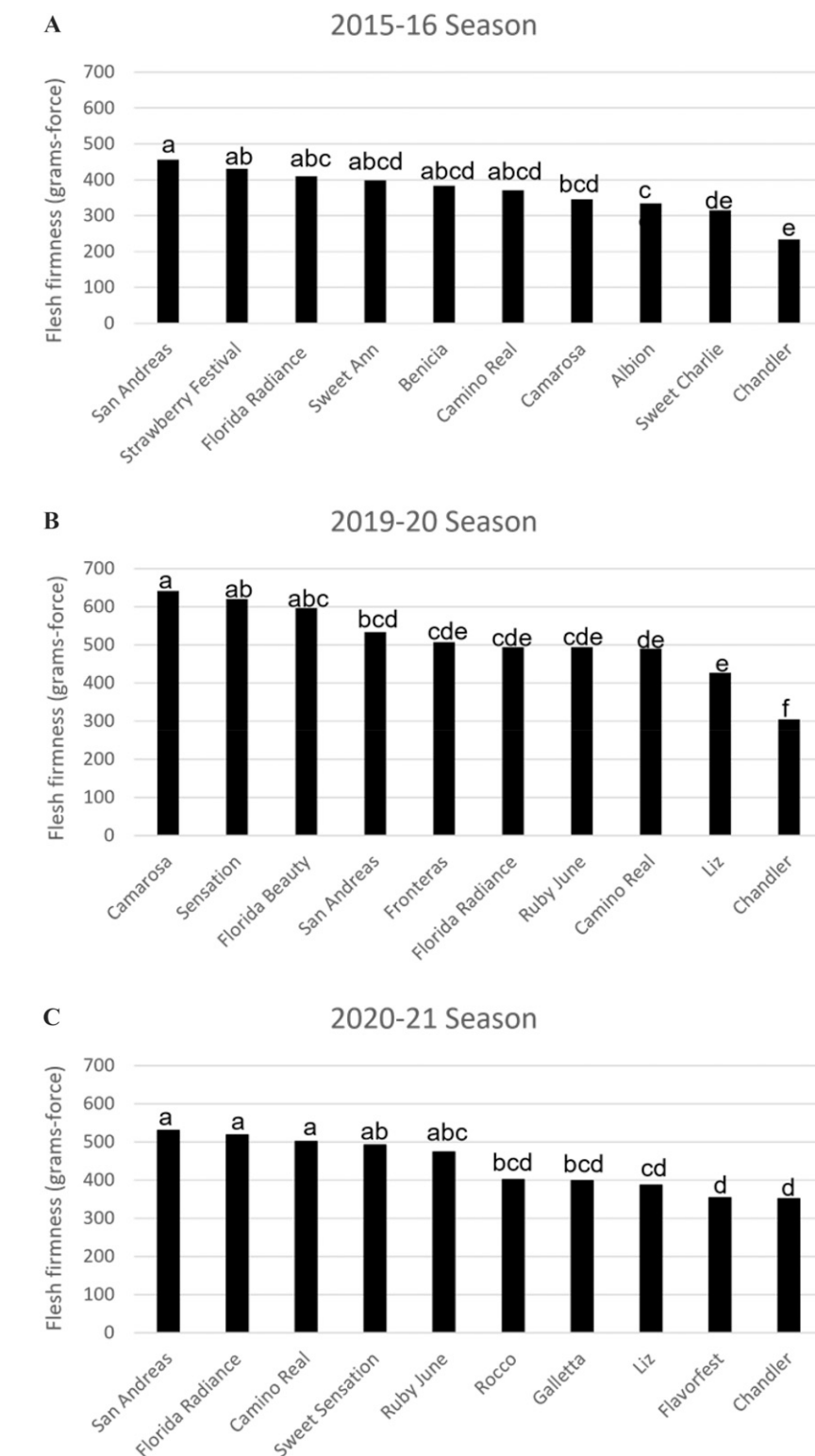


Fig. 6. Fruit firmness (grams-force) of fall-planted strawberry cultivars grown in high tunnels in 2015–16 (A), 2019–20 (B), and 2020–21 (C) seasons at the Southwest Purdue Agriculture Center, Vincennes, IN, USA. Data were analyzed separately by year using analysis of variance. Means labeled by the same letters are not significantly different at $P \leq 0.05$ using Fisher’s protected least significant difference; 1 g-force = 9.8067 mN = 0.0353 ounce-force.

strawberry cultivars growing in an organically managed high tunnel in North Carolina (Gu et al. 2017). In

addition to ‘Ruby June’ and ‘Sweet Charlie’, ‘Camarosa’ also had relatively high sugar content in 2015–16

(9.3%) and 2019–20 (10.2%) seasons. Consistent among the three seasons, Camino Real and Florida Radiance were among the cultivars with the lowest sugar content. ‘Sweet Sensation’ also had relatively low sugar content in both 2019–20 and 2020–21 seasons. Regardless of the different combinations of cultivars evaluated in the three seasons, Chandler consistently had the softest fruit. ‘San Andreas’, ‘Florida Radiance’, ‘Camino Real’, and ‘Sweet Sensation’ had a higher value in flesh firmness (Fig. 6).

Conclusions

The current production system starts at the end of August and lasts until early June the following year. Because a warm-season crop could grow in high tunnels before or after harvesting strawberries, a diversified cropping system involving strawberry and other high-value vegetables is promising for high tunnel production in the north-central United States. Strawberries produced in the current high tunnel system are likely to sell at premium prices because they are harvested at least 4 weeks earlier than strawberry grown in matted-row systems in the same locale. Cultivars including Florida Radiance, Sweet Charlie, Rocco, Sweet Sensation, and San Andreas are most valuable for the system because of their early-ripening patterns. Despite a high yield, ‘Florida Radiance’ had a low sugar content, which may affect consumers’ acceptance of this cultivar. Small fruit sizes of cultivars Chandler and Rocco should also be considered if harvesting labor is limited. Cultivars Galletta, Ruby June, Flavorfest, and Camarosa were ranked low in yield in the high tunnel system despite their demonstrated outstanding yield in the open-field production, suggesting a critical need to select strawberry cultivars targeting specific production system.

Disease resistance, although not addressed in the current study, should be an important factor in selecting cultivars for the high tunnel production system. Future studies are warranted to evaluate the effects of incorporating soil treatments (e.g., solarization, anaerobic soil disinfestation) and cover cropping for suppressing diseases in the soil-based high tunnel system. Two-spotted spider mites were the most important invertebrate pests

observed in the production system. Two-spotted spider mites affected yield in one of the three seasons. No significant difference in cultivars’ tolerance toward this pest was observed in the 2019–20 season (data not shown). Sustainable management strategies including using natural enemies are of great value for successfully managing the pest. Approximately 10% of fruit were misshapen at the beginning of the spring harvest, which may be caused by the environment and a lack of pollination. Although frosts were prevented by using floating rowcovers, low temperatures may delay pollen germination and limit carpel receptivity (Carew et al. 2003). Wind and self-pollination account for most of the pollination in open-field production, but they may be insufficient in the high tunnel system. Introducing insect pollinators to improve yield and reduce misshapen fruit should be evaluated in future studies.

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