Influence of High Tunnel and Field Conditions on Strawberry Growth and Development

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Abstract. Plant growth, yield, and fruit quality of two strawberries (*Fragaria × ananassa* Duch.)—‘Chandler’ and ‘Sweet Charlie’—grown under high tunnels (HTs) were compared with that of field plants during 2002–03 and 2003–04 growing seasons. Plug plants were planted in mid-October 2002 and mid-September 2003 on raised beds covered with black polyethylene mulch. Microclimate of the HTs protected strawberry crowns from winter damage and advanced fruit production 5 weeks earlier than that of plants grown under field conditions. From December to February, average minimum and maximum crown temperatures under the HTs were 5 and 12 °C warmer than those of the field crowns, respectively. The earliest HT fruit were harvested on 7 Apr. 2003 and 11 Mar. 2004. Yield and fruit quality under the HTs were superior to that of field-grown plants. HT plants, especially ‘Sweet Charlie’, bloomed earlier than did field plants, but ‘Chandler’ produced higher yield than ‘Sweet Charlie’ late in the season. Larger fruit with higher soluble solids concentration (SSC) were produced inside the HTs than outside. HT ‘Sweet Charlie’ fruit were sweeter than ‘Chandler’ fruit, but ‘Chandler’ produced larger fruit. Larger leaf area, greater number of leaves and shoot biomass, more branch-crowns, and fewer runners were developed under HTs than field conditions. Total leaf area, leaf production, total shoot biomass, and number of branch-crowns of HT ‘Chandler’ were greater than HT ‘Sweet Charlie’. Results of this study indicate that strawberry plants under HTs were not only precocious, but also produced higher yields and superior quality to that of field plants. HT conditions suppressed runner growth, but enhanced branch-crown development.

Strawberry (*Fragaria × ananassa*) is one of the alternative crops that Kansas farmers are growing to diversify their operations. Early strawberry production provides higher prices (Özdemir and Kaska, 1997a) than late-May or early-June production. One of the many challenges that face strawberry production in Kansas is adverse weather conditions. Winter temperatures in some years might drop below –6 °C, and summer temperatures generally are 38 to 40 °C for 2 to 3 weeks. In addition, late spring frosts, hail damage, and winds of 20 to 50 mph are common. A protective method is imperative, not only for protection from severe weather conditions, but also to produce early, high yield, and quality fruit (Özdemir, 2003; Özdemir and Gündüz, 2004).

High tunnels (HTs) are unheated (Lamont et al., 2002) passive-solar greenhouse structures (Kurata, 1992) used to extend the growing season and protect high-value horticultural crops,

especially when temperatures fall drastically during the fall and winter. A high-tunnel fruit-growing system provides a competitive edge in the market, compared with a field-growing system. The single layer of 6-mil greenhouse-grade polyethylene material (Lamont et al., 2002) that covers the structure provides stable microclimate conditions, which prevents fluctuation of the temperature. Temperatures under HTs are high enough to extend the growing season, improve fruit quality, and protect flowers from early frost damage (Cavins et al., 2000; Wittwer and Castilla, 1995). Early maturity of HT tomatoes was attributed to increases in soil temperatures (Wells and Loy, 1993), which in turn promoted root growth and offset the influence of low night temperatures (Gosselin and Trudel, 1983). Yield of HT sweet pepper was increased by increasing night temperatures with various heating methods (Abou-Hadid and Eissa, 1994). HTs improve light penetration into the canopy, resulting in more uniform irradiance distribution at the foliage, and higher photosynthetic rate, during the growing season (Kurata, 1992). It has been reported that light is reduced by <10% by the plastic layer (Butler et al., 2003).

Early planting of blackberries and raspberries under HTs produced higher yield and between 82% to 98% more marketable fruit than field plants (Demchak, 2003). In Ohio, ‘Chandler’ strawberry produced higher yield per plant and larger fruit than ‘Sweet Charlie’ inside the HTs (Bergeford et al., 1999). About 2 to 3 weeks of early HT strawberry production has

been reported by Önal (2000), compared with production under field conditions. In addition, the microclimate of the HTs accelerated the ripening process of strawberries by 2 weeks, compared with that under field conditions (Demchak, 2003). An extended fruiting season of strawberries under HTs in Turkey has been reported by Özdemir and Kaska (1997a, 1997b). Temperatures under the HTs are usually higher than those in the field, which might enhance the nutritional value of the strawberries. Wang and Zheng (2001) have reported an increase in phenolic acid, flavonols, and anthocyanins that resulted in a significant increase in antioxidant capacity of strawberry plants grown under 25 and 30 °C.

There is increasing interest in double cropping system under HTs with early strawberry production. The objective of this study was to evaluate the efficacy of HTs for strawberry production compared with a field planting system in south-central Kansas. Specific objectives were to compare HTs and field conditions for early production, yield, fruit quality, and plant growth and development of two strawberry cultivars.

Material and Methods

This study was conducted during the 2002–03 and 2003–04 growing seasons in south-central Kansas at the Horticultural Research Center, Wichita. The average minimum temperature in the center is –6 °C, average maximum temperature is 36 °C, wind speed is 10 to 45 mph, and soil texture is fine sandy loam. Soil texture and chemical characteristics were analyzed in the soil-testing laboratory (Kansas State University, Manhattan). Four HTs (Stuppy Greenhouse Manufacturing Inc, North Kansas City, Mo.) were constructed in 2002. Each HT is 6 m wide, 9.6 m long, and 3.6 m high (in the center), providing about 60 m² of total planting area per structure, and HTs are spaced 6 m apart. To maintain stable ventilation, retractable sidewalls are used that extend the length of both sides of the structure. Side walls are manually rolled up as temperatures inside the tunnels exceed 30 °C. Each tunnel is covered with a single layer of 6-mil (0.153-mm) greenhouse-grade polyethylene material (Stuppy Greenhouse Manufacturing). Field plots had similar dimensions as the HTs. Strawberry growth and productivity under the HTs was compared with those of field plots. ‘Chandler’ and ‘Sweet Charlie’ were selected as the new and promising strawberry cultivars for south-central Kansas.

Greenhouse-rooted plug plants (Davon Crest Farms LLC, Hurlock, Md.) were hand planted in mid-October 2002 and mid-September 2003. The experiment was a complete randomized factorial arrangement of 2 environments (HTs and field) and 2 cultivars (‘Chandler’ and ‘Sweet Charlie’) with 4 replications. Each replication consisted of 2 beds per cultivar, giving a total of 4 beds per replication. Each bed consisted of 2 rows, each row with 12 plants, which totaled 48 plants per cultivar per replication. From each cultivar, 8 plants (4 plants per bed) were destructively harvested monthly for cold-hardi-

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Table 1. Soil chemical and physical properties inside the high tunnels (HTs) and outside (field) at the Horticultural Research Center, Wichita, Kan.

Property	HT	Field
pH	6.7	7.0
Organic matter (%)	1.2	1.1
Phosphorus (ppm)	42	27
Calcium (ppm)	929	978
Potassium (ppm)	92	76
Magnesium (ppm)	100	109
Copper (ppm)	0.4	0.5
Iron (ppm)	32	20
Manganese (ppm)	4.2	4.1
Zinc (ppm)	8.1	5.2
Texture		
Sand (%)	71	70
Silt (%)	26	25
Clay (%)	4	5

ness evaluation. Two outer rows were guard plants. Plants were spaced at 45×45 cm within and between the plants in rows each 6 m long. Plants were planted on raised beds (70 cm wide) with 1.5 m centers covered with black polyethylene mulch (Berry Hill Irrigation, Inc., Buffalo Junction, Va.). The black mulch was applied to reduce weed pressure and increase soil temperature. Beds were irrigated with a drip irrigation system installed under the plastic mulch, with one emitter per plant using a drip irrigation tube that delivered $1.29 \text{ L} \cdot \text{h}^{-1}$ (T-Tape; DripWorks, Willits, Calif.). Before

Fig. 1. Mean minimum and maximum daily ambient temperatures in 2003–04 ($^{\circ}\text{C}$) from December to March inside the high tunnels (HTs) (●) and outside (field) (○). High tunnels data are means of three heights from the middle of HTs; outside data are measurements at 182.9 cm height.

planting, beds were fertilized with 454 g of $\text{N}/92.9 \text{ m}^2$ of 13N–13P–13K. Two weeks after planting, plants were fertigated with CaNO_3 (9–0–0–11) at 200 ppm N, 8N–45P–14 K at 30 ppm P, and 5N–11P–26K at 40 ppm K. Plants inside and outside the tunnels were protected during the winter with a floating row-cover ($50.86 \text{ g} \cdot \text{m}^{-2}$ heavy-weight frost protection; Berry Hill Irrigation Inc.) when temperature dropped below -7°C .

Sensors (CS500; Campbell Scientific, Logan, Utah) were used to measure air temperatures inside and outside the HTs. Daily maximum and minimum air temperatures were recorded at 91.4, 182.9, and 274.3 cm inside the HTs in the middle and at the corners of each tunnel. Temperature outside the HTs was measured at 182.9 cm height from the soil surface. Copper-constantan thermocouples placed in one row per cultivar inside and outside the HTs were used to measure crown temperature; soil temperature was measured at 10.2 cm depth. Data from inside and outside the HTs were recorded every 15 min using a datalogger and multiplexer (CR10X and AM25T; Campbell Scientific).

During the winter and early spring, crown injury was evaluated on the basis of crown browning. Eight plants per cultivar were removed from each tunnel and field plot, and kept in the cold room at 4°C for 24 h before crown injury was visually evaluated under the microscope; $>25\%$ browning was considered a dead crown. Fruit were harvested weekly from the HTs and field plots, starting 7 Apr. 2003 and 11 Mar. 2004. Marketable fruit were separated from the unmarketable fruit

by the presence of gray mold (*Botrytis cinerea*) or leather rot (*Phytophthora cactorum*), deformities, or physical damage. Numbers of marketable and unmarketable fruit were recorded, and yield per plant was calculated. Average fruit weight was based on weight of 25 berries, and weight of the largest fruit was recorded. Percentage of soluble solids concentration (SSC) of juice extracted from three randomly selected fruit was determined by using a hand-held refractometer (Spectrum Technologies, Inc, Plainfield, Ill.).

Plant growth and development inside and outside the HTs were measured at the last harvest. Total leaf area (LA) per plant was measured with a leaf area meter (LI-3100; LI-COR Inc., Lincoln, Neb.). Numbers of leaves, branch-crowns, and runners per plant were recorded. Leaves and shoots were dried at 70°C for 72 h, and total shoot biomass was determined.

Data were analyzed using standard analysis of variance (ANOVA) (SAS Institute, 1990). Differences among means were tested by Fisher's protected least significant difference (LSD) ($P = 0.05$). Spearman rank correlation coefficients (r) measuring correlation coefficients between parameters were calculated.

Results and Discussion

Soil properties and mineral content are listed in Table 1. Soil type in the Wichita

Fig. 2. Mean minimum and maximum strawberry crown temperatures in 2003–04 ($^{\circ}\text{C}$) from December to March inside the high tunnels (HTs) (●) and outside (field) (○).

Horticultural Center is Canadian fine sandy loam, with a high percentage of sand and a low percentage of clay, which makes it suitable for strawberry growth. Strawberries were planted following vegetable crops, and soil was amended and cultural practices were followed according to recommendations (Kadir, 2003).

Although temperature was recorded for both seasons, equipment malfunction during part of the 2002–03 season prevented complete data collection. Thus, Figs. 1 and 2 represent data from 2003–04 season. During the winter, warm temperatures inside the tunnels promoted plant growth and early flowering, whereas field plants were dormant. Average minimum air temperature from December to March inside the HTs was 1 to 2 °C higher than field temperatures (Fig. 1). There were 13 to 14 °C differences in maximum temperature in December and January and 3 °C differences in February, but differences diminished in March. There was no significant difference in crown minimum or maximum temperatures between the two cultivars inside the HTs from December to March (data not shown). Nevertheless, there were differences between crown temperatures inside the tunnels and outside (Fig. 2). Differences between HT and field minimum temperatures in December and January were 2 and 7 °C, respectively, whereas differences in maximum temperatures were 15 to 17 °C. In February, the differences in minimum and maximum temperatures were 4 to 6 °C, respectively. Minimum and maximum temperatures inside the HTs and outside were similar in March. The heat-holding characteristic of HTs has been investigated, and differences of 11 °C between inside the tunnels and outside have been reported during the coldest season in Japan (Ogura et al., 1984).

Regardless of the cultivar, HT crowns were more protected from winter damage than field crowns (Fig. 3). In the 2002–03 season, HTs protected 100% of the crowns from winter damage, although no significant injury was observed in field crowns in December or January. As plants started to deacclimate in February, 14% of the crowns were injured by winter temperatures. Total deacclimation in March caused damage to 20% of the field crowns. Plants in the 2003–04 season lacked sufficient cold acclimation because of the mild winter (data not shown). This might have caused early crown deacclimation and injury inside and outside the tunnels from occasional cold temperatures. Nevertheless, injury to the HT crowns from December to January was not significant, compared with injury to the field crowns. In December, 15% of the field crowns were injured, compared with 1% of the HT crowns. As plants deacclimated in March, 33% of the field crowns were injured, compared with 5% of the HT crowns. These results indicate that the microclimate of the HTs has a positive effect on strawberry plants by protecting the crowns from damage during cold or mild winter temperatures. An increase in the rate of accumulation of growing-degree days (GDDs) has been related to early crop growth in the HTs (Waterer, 2003).

HT conditions enhanced early production in the 2002–03 (Fig. 4) and 2003–04 (Fig. 5) seasons. Fruit were harvested weekly, starting with HT plants in 7 Apr. 2003 and 11 Mar. 2004. Field fruit were harvested 6 May 2003 and 28 Apr. 2004. Results agree with earlier reports that HT conditions produced early strawberries (Özdemir and Kaska, 1997a, 1997b). Marketable fruit and fruit quality in both seasons were greater inside the tunnels than outside. ‘Sweet Charlie’ under the tunnels in both years bloomed 2 to 3 weeks earlier than ‘Chandler’ (data not shown). ‘Sweet Charlie’ has been reported to be the earliest cultivar, with the highest early yield, compared with the other strawberry cultivars (Özdemir et al., 2001; Özdemir and Gündüz, 2004), including ‘Chandler’ (Özdemir, 2003). In 2003, ‘Sweet Charlie’ produced more marketable fruit per plant in the second week than ‘Chandler’ (Fig. 4). Nevertheless, the latter produced significantly more fruit after week 4. Increased number of marketable fruit for HT ‘Chandler’ late in the season was linear and significantly higher than that of ‘Sweet Charlie’, with 32% more fruit in the last week. Regardless of the cultivar, field plants were harvested once, about 1 month later than HT plants, with low yield.

The purpose of this study was to produce quality and high value strawberries early in the spring, when market demands are high. In addition, plant and introduce a second high value crop early to the market. Because strawberry was part of double-cropping system inside the HTs, strawberry experiments were terminated before production inside and outside the HTs was finished, and a vegetable crop was planted. Harvest was terminated after 6 weeks in 2003 and after 10 weeks in 2004. Early termination of the experiment resulted in lower yield per plant than those in earlier reports of strawberries under HTs (Özdemir et al., 2001; Özdemir and Gündüz, 2004) where production was carried out to completion. For the purpose of using HTs for double cropping system, planting dates for early and high value strawberry production should be adjusted.

Throughout harvest, HT ‘Chandler’ produced bigger fruit than ‘Sweet Charlie’, except for the first week (Fig. 4). Average fruit weight for ‘Chandler’ in week 3 was 22 g, compared with 17 g for ‘Sweet Charlie’, and the largest fruit was 36 g, compared with 27

g for ‘Sweet Charlie’. Larger berries of HT ‘Chandler’ than ‘Sweet Charlie’ has been previously reported (Özdemir, 2003). In this study, a decline in fruit weight after the third week was due to the plant investing in higher yield, although it was reported that the decline was due to development of branch-crown and/or to the decline in storage carbohydrate (Anderson and Guttridge, 1982). Early production and large fruit of strawberry on raised beds inside the tunnels are the result of warm microclimate conditions inside the tunnels (Özdemir and Gündüz, 2004).

Although ‘Chandler’ produced more marketable fruit and larger berries than ‘Sweet Charlie’, the latter had higher SSC. ‘Sweet Charlie’ fruit had an average of 9.7% SSC, compared with 8% for ‘Chandler’; the maximum SSC was in week 5 when ‘Sweet Charlie’ had 11% SSC, compared with 9% for ‘Chandler’. These values are generally larger than the maximum refractometric index (RI) values that contribute to high taste quality of strawberries (Alavoine and Crochon, 1989). Increase in SSC from 8.5% to 9.6% in ‘Chandler’ and 9.7% to 11% for ‘Sweet Charlie’ from week 3 to week

Fig. 3. Injured strawberry crowns inside the high tunnels (HTs) (●) and outside (field) (○) from December to March during 2002–03 and 2003–04 grown seasons. Crown injury was evaluated on the basis of crown browning. Browning >25% was considered an injured crown. Values are means of eight plants planted 45 cm apart within the row. Vertical lines through data points are standard errors; values smaller than symbols are not shown.

5 was due to increased temperatures inside the tunnels (data not shown). This agrees with earlier reports that high temperatures under HTs increase sugar content (Kaska et al., 1986; Ruiz et al., 1997). 'Sweet Charlie' is known to have higher SSC than other cultivars, including 'Chandler' (Özdemir, 2003). It is reported that SSC of 'Sweet Charlie' is relatively high early in the season, but decreases during the peak of fruit production (Chandler et al., 2003).

Because of earlier planting in 2003–04 season, HT harvest started a month earlier than 2002–03 season and extended for 10 weeks,

at weekly intervals (Fig. 5). In addition, field harvest was extended for 2 to 3 weeks, depending on the cultivar, compared with one harvest in 2002–03 season. HT 'Sweet Charlie' did not perform as well as 2002–03 season, due to the small size of the plug plants, but it produced earlier and more fruit than 'Chandler' in the first 7 weeks. 'Chandler' yield was linear after week 7, an average of 138% increase in number of fruit was recorded compared with that of 'Sweet Charlie'. Field 'Sweet Charlie' produced 1 week earlier than 'Chandler', but number of fruit of 'Chandler' was more than twice than that of 'Sweet Charlie' in week 10. 'Chandler' and 'Sweet Charlie' had maximum average fruit weights of 19 g and 15 g, respectively, in week 8. The largest fruit for HT 'Chandler' was 33 g in week 9, compared with 28 g for 'Sweet Charlie' in week 8. Even field plants of both cultivars produced sizable fruit. Fruit SSC, both inside and outside the tunnels, showed a similar pattern to that of 2002–03

season (Fig. 4). Field and HT 'Sweet Charlie', throughout the harvest, produced sweeter berries than 'Chandler'. Maximum SSC of HT 'Sweet Charlie' fruit was 12% in week 10, 28% higher than that of HT 'Chandler'. Although SSC of HT and field 'Sweet Charlie' were higher than that of 'Chandler', SSC of HT 'Sweet Charlie' in week 9 was 19% higher than that of field 'Sweet Charlie'. These results suggest that HT microclimate has a positive effect not only on precocity, but also on SSC and fruit size of strawberries.

Yields per plant for 2002–03 and 2003–04

Fig. 4. Marketable fruit, largest fruit, average fruit weight, and soluble solids concentration (SSC) of high tunnel (HT) 'Chandler' (●), HT 'Sweet Charlie' (▲), field 'Chandler' (○), and field 'Sweet Charlie' (△) strawberries during 2002–03 growing season. Values are means of 16 plants planted 45 cm apart within the row. Vertical lines through data points are standard errors; values smaller than symbols are not shown.

Fig. 5. Marketable fruit, largest fruit, average fruit weight, and soluble solids concentration (SSC) of high tunnel (HT) 'Chandler' (●), HT 'Sweet Charlie' (▲), field 'Chandler' (○), and field 'Sweet Charlie' (△) strawberries during 2003–04 growing season. Values are means of 16 plants planted 45 cm apart within the row. Vertical lines through data points are standard errors; values smaller than symbols are not shown.

are shown in Fig. 6. In 2003, total production per plant from week 4 to week 6 of HT ‘Chandler’ was 138 g, compared with 104 g for ‘Sweet Charlie’. In 2004, maximum production was between week 8 and 10 for both cultivars. Low yield of ‘Sweet Charlie’ was due to the small size of the plug plants planted in 2003. In 2004, field ‘Chandler’ in week 10 produced 130% higher yield than field ‘Sweet Charlie’.

Numbers of pink and green fruit of both cultivars inside the tunnels and outside at the end of the experiments are presented in Table 2. Both cultivars inside the HTs in 2003 and 2004 seasons had more pink and green fruit than field plants. ‘Chandler’ in 2003 had more green fruit than ‘Sweet Charlie’. In 2004, HT and field ‘Chandler’ had more pink fruit than ‘Sweet Charlie’. These results indicate that

terminating the experiment was premature, and had the harvest been extended beyond 6 or 10 weeks in 2003 or 2004, respectively, there would have been more yield from ‘Chandler’ than ‘Sweet Charlie’.

Fruit rot, deformed, or physically damaged fruit were considered unmarketable (Table 3). Regardless of the cultivars, field plants in 2003 did not produce a significant number of unmarketable fruit. Air temperatures under HTs in week 5 and 6 were 36 and 34 °C, respectively (data not shown), which increased the number of unmarketable fruit for both cultivars. Unmarketable yield per plant for both cultivars corresponded to the number of unmarketable fruit. The highest unmarketable yield in 2002–03 of HT ‘Chandler’ was in week 5, whereas the lowest unmarketable yield was

in week 1. Similarly, the highest unmarketable yield for ‘Sweet Charlie’ was in weeks 5 and 6. In 2004, there were more unmarketable fruit produced from HT ‘Chandler’, compared with that of HT ‘Sweet Charlie’, especially late in the season, which corresponded to higher unmarketable yield. Nevertheless, field ‘Sweet Charlie’ produced more unmarketable fruit and higher yield in the last 2 weeks than ‘Chandler’.

‘Chandler’ and ‘Sweet Charlie’ growth inside and outside the HTs is shown in Table 4. In general, HTs promoted more growth than field conditions. In 2003, HT and field ‘Chandler’ plants were more vigorous than ‘Sweet Charlie’ plants. Total LA, total shoot biomass, and number of leaves and branch-crowns of ‘Chandler’ were greater than that of ‘Sweet Charlie’. Regardless of the cultivar, HT microclimate was more conducive to branch-crown development, whereas field conditions enhanced runner development. ‘Chandler’ developed more branch-crowns than ‘Sweet Charlie’ under both conditions. No varietal difference in number of runners under either condition was determined. LA of a HT ‘Sweet Charlie’ plant was not significantly different than that of a field plant, which corresponded to similar total shoot biomass and number of leaves. This indicates that assimilates of HT ‘Sweet Charlie’ were diverted to early fruit production instead of vegetative growth. On the other hand, HT ‘Chandler’, being the late producer, diverted most assimilates early in the season to vegetative growth that supported production late in the season. Regardless of the cultivar, HT microclimate might have diverted most of assimilates for early branch-crown and reproductive stage development, whereas assimilates under field conditions were initially used for vegetative growth. In 2004, no varietal differences under the HTs in LA, total shoot biomass, or number of runners were observed, but ‘Chandler’ produced more leaves and branch-crowns than HT ‘Sweet Charlie’. Greater total shoot biomass of field ‘Sweet Charlie’ was observed because it developed more runners than ‘Chandler’, whereas field ‘Chandler’ produced more branch-crowns than ‘Sweet Charlie’. This indicates that assimilates of field ‘Sweet Charlie’ in 2004 was diverted toward more runners rather than toward branch-crown development. These results indicate that the HT microclimate not only shifted assimilates early toward reproductive stages, but also altered the growth and development of plant parts to produce more branch-crowns for earlier and higher yield than those under field conditions, although varietal differences existed.

Fig. 6. Yield of high tunnel (HT) ‘Chandler’ (●), HT ‘Sweet Charlie’ (▲), field ‘Chandler’ (○), and field ‘Sweet Charlie’ (△) strawberries during 2002–03 and 2003–04 growing seasons. Values are means of 16 plants planted 45 cm apart within the row. Vertical lines through data points are standard errors; values smaller than symbols are not shown.

Table 2. Pink and green fruit of ‘Chandler’ and ‘Sweet Charlie’ harvested 17 May 2003 and 27 May 2004 from the high tunnels (HTs) and field plots during 2002–03 and 2003–04 growing seasons.

Cultivar	2002–03				2003–04			
	Pink fruit/plant		Green fruit/plant		Pink fruit/plant		Green fruit/plant	
	HT	Field	HT	Field	HT	Field	HT	Field
‘Chandler’	2.3 ^y a ^x	0.4 b	8.3 a	0.3 c	18 a	13 b	8.8 a	3.7 b
‘Sweet Charlie’	1.6 a	0.1 b	5.0 b	0.1 c	8.3 c	1.3 d	8.1 a	0.1 c

^yLess than 25% red.

^xMeans of three plants planted 45 cm apart within the row.

^zData subjected to analysis of variance and means within columns labeled by different letters are significantly different at $P \leq 0.05$ using Fisher’s protected least significant difference (LSD).

Correlations between yield, fruit quality, and growth parameters of strawberry plants are shown in Table 5. It is not surprising that yield was positively related to number of fruit, average fruit weight, and largest fruit weight. Among the growth parameters, LA was positively related to number of runners ($r = 0.88$) and branch-crown development ($r = 0.80$), but number of branch-crowns was negatively related to number of runners ($r = -0.45$). This suggests that crown development may antagonize runner development under HTs. The positive relation among yield, fruit quality, and plant growth parameters was attributed to the positive relation of LA to yield, average fruit

weight, and largest fruit weight. The positive relation between LA and yield under HTs was confirmed by an earlier report. An increase in leaf area index of pepper plants under HTs was related to a pepper yield increase (Medany et al., 1990). Runner development was unrelated to the yield or fruit-quality parameters. Nevertheless, the number of branch-crowns was related to yield ($r = 0.81$), average fruit weight ($r = 0.65$), largest fruit weight ($r = 0.61$), and SSC ($r = 0.51$). The association of yield and fruit quality to growth parameters shows the positive influence of branch-crown development and greater LA on yield and quality of HT strawberry fruit. Strawberry yield has been reported

to be related to the number of mother plants and crowns (Wilson and Dixon, 1988).

This is a comprehensive study comparing strawberry yield and vegetative growth responses to the microclimate of HTs and field conditions. Regardless of the cultivar, these results indicate that HTs protected strawberry plants from winter damage, provided a favorable microclimate for plant growth, and produced earlier, with higher yield and higher quality fruit than field conditions. HTs enhanced branch-crown development, which was positively related to strawberry yield and fruit quality. Field conditions enhanced runner development, which was not related

Table 3. Unmarketable fruit and yield of 'Chandler' and 'Sweet Charlie' inside the high tunnels (HTs) and outside (field) during 2002–03 and 2003–04 growing seasons.

Week	'Chandler'				'Sweet Charlie'			
	Fruit/plant		Yield (g/plant)		Fruit/plant		Yield (g/plant)	
	HT	Field	HT	Field	HT	Field	HT	Field
2002–03								
1	0.1 ^{zy}	0.0	0.3	0.0	1.6	0.0	1.6	0.0
2	2.4	0.0	2.9	0.0	1.9	0.0	1.5	0.0
3	2.1	0.0	1.8	0.0	2.4	0.0	2.0	0.0
4	1.3	0.0	1.4	0.0	1.3	0.0	1.2	0.0
5	6.0	0.0	6.2	0.0	5.3	0.0	3.6	0.0
6	4.3	0.4	2.5	0.3	5.6	0.3	3.5	0.2
LSD _(0.05)	1.0		0.9		1.0		0.9	
2003–04								
1	0.3	0.0	1.9	0.0	4.0	0.0	25	0.0
2	0.8	0.0	6.4	0.0	3.6	0.0	22	0.0
3	3.4	0.0	25	0.0	4.1	0.0	24	0.0
4	3.8	0.0	25	0.0	4.7	0.0	25	0.0
5	0.7	0.0	5.8	0.0	1.9	0.0	1.2	0.0
6	2.8	0.0	17	0.0	1.9	0.0	8.6	0.0
7	3.8	0.0	24	0.0	0.8	0.0	3.6	0.0
8	4.4	0.0	20	0.0	3.0	0.0	18	0.0
9	6.2	2.2	44	12	2.2	12.4	8.8	77.7
10	7.0	4.3	34	23	2.4	11.4	11.7	43.7
LSD _(0.05)	1.7		5.2		1.7		5.2	

^zMeans of 16 plants planted 45 cm apart within the row.

^yData subjected to analysis of variance and mean separation within columns performed by least significant difference (LSD) at $P \leq 0.05$.

Table 4. Total leaf area (LA), total shoot biomass, and numbers of leaves, runners and branch-crowns of 'Chandler' and 'Sweet Charlie' inside the high tunnels (HTs) and outside (field) during 2002–03 and 2003–04 growing seasons.

Cultivar	LA (cm ²)		Shoot biomass (g)		Leaves (no.)		Runners (no.)		Branch crowns (no.)	
	HT	Field	HT	Field	HT	Field	HT	Field	HT	Field
2002–03										
'Chandler'	1454 ^a	1140 ^b	15.1 ^a	13.6 ^{ab}	68 ^a	55 ^b	0.8 ^b	2.6 ^a	3.3 ^a	1.4 ^c
'Sweet Charlie'	619 ^c	717 ^c	12.2 ^{bc}	11.2 ^c	32 ^c	35 ^c	0.6 ^b	2.3 ^a	2.4 ^b	1.0 ^d
2003–04										
'Chandler'	1000 ^a	594 ^c	10.1 ^a	7.9 ^c	75 ^a	40 ^b	0.1 ^c	4.3 ^b	3.7 ^a	3.0 ^{ab}
'Sweet Charlie'	882 ^{ab}	705 ^{bc}	9.7 ^a	8.2 ^b	45 ^b	35 ^b	0.6 ^c	6.5 ^a	2.1 ^{bc}	1.7 ^c

^aMeans of three plants planted 45 cm apart within the row.

^bData subjected to analysis of variance and means within columns labeled by different letters are significantly different at $P \leq 0.05$ using Fisher's protected least significant difference (LSD).

Table 5. Pearson correlation coefficient (r) and statistical probabilities for fruit number, yield, average fruit, largest fruit, soluble solids concentration (SSC), total leaf area (LA), runner number, and branch-crown number of high-tunnel (HT) strawberry plants.

Parameter	Yield (g/plant)	Avg fruit (g)	Largest fruit (g)	SSC (%)	LA (cm ²)	Runners (no.)	Branch crowns (no.)
Fruit	0.95**	0.74**	0.70**	0.36 ^{NS}	0.95**	-0.32 ^{NS}	0.94**
Yield (g/plant)		0.68**	0.89**	0.44 ^{NS}	0.82**	-0.25 ^{NS}	0.81**
Average fruit (g)			0.68**	0.01 ^{NS}	0.69**	-0.05 ^{NS}	0.65**
Largest fruit (g)				0.23 ^{NS}	0.51**	-0.17 ^{NS}	0.61 ^{NS}
SSC (%)					0.03 ^{NS}	0.02 ^{NS}	0.51 ^{NS}
LA (cm ²)						0.88**	0.80**
Runners (no.)							-0.45*

^{NS},**Nonsignificant, significant at $P \leq 0.05$ or 0.01, respectively.

to the yield or fruit quality. Therefore, the microclimate of HTs helped shift assimilates for early reproductive stages development, whereas field conditions were more conducive for vegetative growth. This report indicates that HT strawberry has a great potential for early production, quality fruit, and protection from low temperatures, compared with conventional strawberry production systems. In addition, early strawberries to the market can be sold for a high price in March or early April, and contribute to farmer's profitability by providing a longer market window in south-central Kansas.

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