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Influence of high tunnel conditions and cultivars on the growth, yield, and fruit quality of strawberry in northern Türkiye

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Abstract: This study was carried out in Samsun, in the northern part of Türkiye. Short-day cultivars Amiga, Fortuna, Rubygem, Festival, and Camarosa and day-neutral cultivars Albion, Monterey, Sweet Ann, and San Andreas were evaluated for harvest period, fruit yield and quality, and vegetative growth under open field and high tunnel conditions. Fortuna, Festival, and Rubygem were the earliest cultivars and Sweet Ann the latest cultivar under both conditions. Harvest started about 1 month earlier under high tunnel conditions due to the higher air and soil temperatures than the open field. The harvest period lasted 16 to 21 weeks in the open field and 20 to 22 weeks in the high tunnel. In the open field, the harvest period lasted about 16 to 18 weeks for short-day cultivars and 16 to 21 weeks for day-neutral cultivars. Thus, the cool summers of northern Türkiye led to a long harvest season not only for day-neutral cultivars but also short-day cultivars. The high tunnel did not affect yield-related parameters. Monterey, Albion, and Fortuna showed the best performances in terms of total, marketable, and percent marketable yield. Despite the high total and marketable yield, the marketability levels of Sweet Ann and Rubygem were lower than those of the other cultivars. Production system × cultivar interactions showed that cultivar selection was important in both production areas. In the open field the Monterey, Sweet Ann, and Albion and in the high tunnel the Fortuna, Rubygem, Festival, Amiga, and Monterey cultivars performed best in terms of yield. Production system, cultivar, and production system × cultivar interactions affected fruit quality and growth. High tunnel conditions generally affected fruit quality positively. Numbers of crowns and runners and plant biomass in strawberry plants grown in the open field were significantly higher than those of plants grown in the high tunnel. Thus, open field conditions were more conducive for plant growth. Day-neutral cultivars are characterized by high productivity and long harvest seasons in the northern areas of Türkiye.

Key Words: *Fragaria* × *ananassa*, protected agriculture, production, fruit characteristics, plant development

1. Introduction

Strawberry (*Fragaria* × *ananassa*) is widely spread around the world and 9,175,284.43 tons of strawberries were produced worldwide in 2021.[1] Kaska (1997) reported that most strawberry growers are small land-holders and strawberry cultivation in Türkiye is done as a family business; however, this situation has shifted towards larger commercial enterprises over time (Demirsoy and Serçe, 2016). Türkiye was the third largest strawberry producer in the world with 669,195 tons in 2021,[1] and 38% of the total production is undertaken in high and low tunnels and in the southern part of Türkiye. While early production was the objective in protected structures in the past, recently, year-round strawberry production is the target.

A high tunnel provides benefits to growers by improving earliness and giving them competitive advantages in the market, reducing the use of sprinkler irrigation for freeze safety, lowering fuel or energy costs, and reducing the incidence of foliar and fruit diseases and fruit damage compared to open field production. Higher temperatures in high tunnels compared to those of open fields might enhance the nutritional value of the strawberries (Kadir et al., 2006; Salamé-Donoso et al., 2010). Harvesting in the spring begins 3 to 5 weeks earlier than typical for the same cultivars grown in open fields, depending on year (Demchak, 2009). High tunnels ensure an extended fruiting season for strawberries (Özdemir and Kaska, 1997; Medina et al., 2011; Rowley et al., 2011; Gude et al., 2018b). Early yields increased by up to 54% and higher total marketable yields with fruit weight increments of up to 63% were determined in high tunnels in contrast to open fields (Salamé-Donoso, 2010). Although high tunnels

1 Food and Agriculture Organization of the United Nation (2022). FAOSTAT [online]. Website https://www.fao.org/faostat/en/#data/QCL [accessed 10 March 2023].

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or protected structures are widely used in strawberry cultivation around the world, their effects on strawberry production still need to be investigated due to climate, cultivar, and production system differences. Strawberry production in Türkiye has typically been concentrated in the southern regions. However, in recent years, production has spread across the country. The Black Sea coastal areas are sheltered by high mountains and the area has mild winters and humid cool summers. Strawberry growing is newly developing in the region. There is an increasing interest in growing day-neutral strawberries in particular, as the region's cool summer and mild autumn climate allows day-neutral strawberries to bloom from spring to late autumn. However, the rains during the harvest season and relatively low temperatures during winter and early spring are challenges for growing strawberries in the region. High tunnels or protected cultivation may be a solution to this problem. However, there is a need to investigate the effects of high tunnel cultivation on microclimate, yield, quality, extension of the harvest season, and variety adaptation. This study aimed to evaluate the efficacy of high tunnel and open field strawberry production on harvest season, yield, fruit quality, and plant growth of some short-day and day-neutral strawberry cultivars in North Anatolia.

2. Materials and methods

2.1. Experimental site, planting materials, soil, and climatic conditions

The experiment was carried out in an experimental field located at 41°22´N, 36°11´E and 115 m above sea level and belonging to the Agriculture Faculty of Ondokuz Mayıs University in Samsun Province in the northern part of Türkiye in the 2014-2015 growing season. In the experiment, Rubygem, Festival, Fortuna, Amiga, and Camarosa as short-day (SD) cultivars and Monterey, Albion, San Andreas, and Sweet Ann as day-neutral (DN) cultivars were used in two production systems (open field and high tunnel). Two adjacent high tunnels with dimensions of 6 m × 6 m × 20 m (height, width, and length, respectively) and top-side ventilation were used. Tunnel roofs were covered with polycarbonate corrugated sheets of 1 cm in thickness with UV additive and their sides were covered with clear polyethylene with UV, IR, and AF additives in mid-November 2014. After the temperature started to rise above 25 °C, the tunnel was shaded with shading material with 50% light transmittance on June 17. Soil pH values of the experimental area were 7.41 and 6.96 in the high tunnel and open field, respectively. The soil structure of both the high tunnel and open field was sandy-clay loam.

The experimental area has a mild climate. In the area, the hottest months are July and August and the coldest months are January and February based on long-term data. Average daily air temperatures and soil temperatures at soil depth of approximately 10 cm were recorded at hourly intervals using data loggers (Kistock KH 200) for both experimental treatments (Figures 1 and 2). The light intensity in the high tunnel and open field was also measured with a quantum meter (MQ-100X, Apogee Instruments, Logan, UT, USA) from August 15, 2014, through July 3, 2015, excluding January and February (Figure 3).

2.2. Establishment and management

The bottoms of the planting beds were 90 cm wide, the upper surfaces were 70 cm wide, and the heights were 30 cm. During the preparation, 0.5 t ha^{-1} farmyard manure

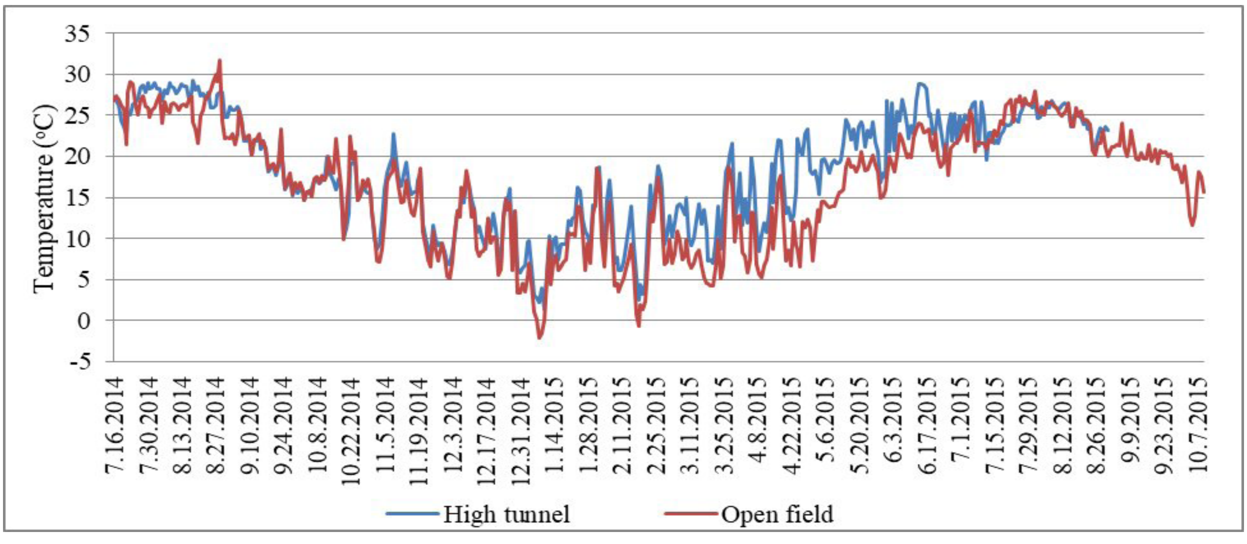

Figure 1. Temperatures of the experimental systems.

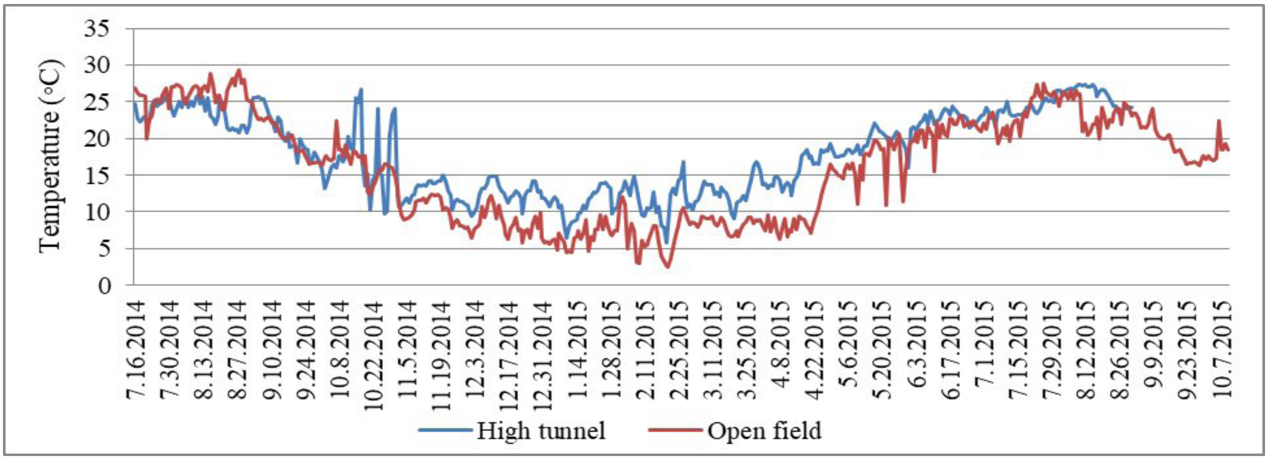

Figure 2. Soil temperatures of the experimental systems.

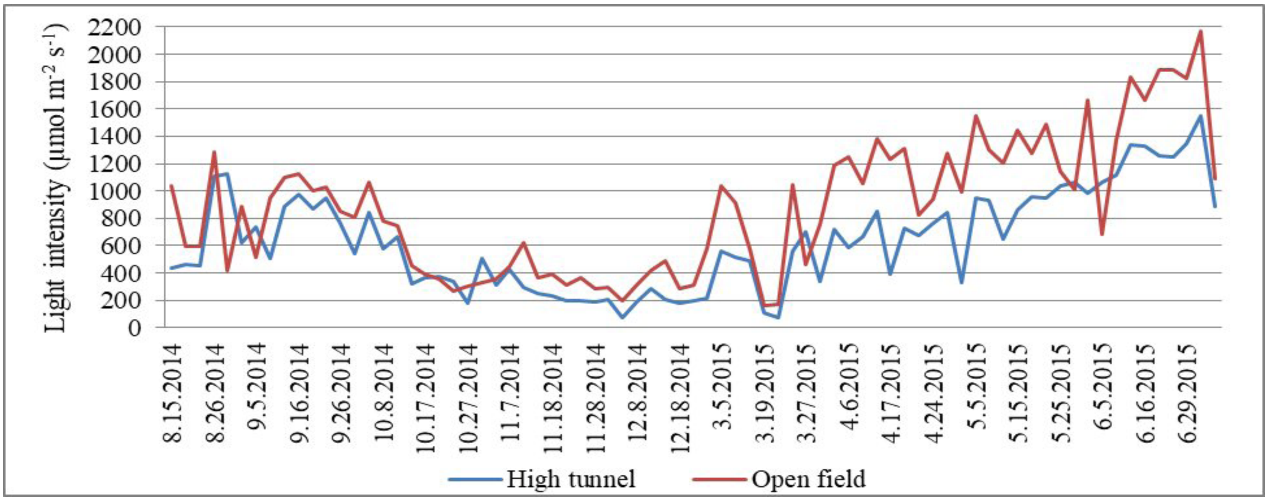

Figure 3. Light intensities of the experimental systems.

was mixed with the soil. A single trickle irrigation system with emitters 25 cm apart was installed. Beds were covered with silver/black polyethylene mulch after the plants were pruned at the end of the fall growth period. Dormant bare root plants (frigo plants) were planted on July 7 and 8, 2014, in the high tunnel and open field. Plants were placed in double rows with a triangle planting system with 30 cm of spacing between rows and in rows. The flowers were removed after planting until autumn. For plant nutrition, ammonium sulfate was applied at 2 g plant^{-1} on August 22 and September 16 and as 4 g plant^{-1} at the beginning of flowering in spring time. Disease and pest control was achieved by following current recommendations for strawberries.

2.3. Data collection

Ripe fruits were harvested one or two times per week from each plot. Total yield (g plant^{-1}) was calculated by dividing the total fruit production amount obtained from each plot by the number of plants in the plot. Fruit yield data did not include fruits damaged due to disease, pests, or rain. Fruits heavier than 6 g, with uniform color and shape and free of mechanical defects, were classified as marketable (g plant^{-1}) (Pérez de Camacaro et al., 2002). For percent marketable yield, the marketable yield was multiplied by 100 and then divided by total yield. Fruit weight (g) was calculated by dividing the total plot yield by the number of fruits harvested from the plot. For soluble solids, titratable acid, and fruit firmness data, four fully red marketable fruits were harvested at 2-week intervals. Soluble solid content (SSC) (%) was determined in fruit juice with a digital refractometer (Abbe refractometer, Carl-Zeiss, Jena, Germany). Titratable acid content (TAC) (%) was measured by titration with 0.1 NaOH as an equivalent of citric acid. Fruit firmness (kg cm^{-2}) was measured from two opposite sides of the equatorial region of the fruits with a digital penetrometer (FHT 200, Extech Instruments, Nashua, NH, USA) using a 3-mm plunger as the maximum penetration force (kg cm^{-2}) reached during tissue breakage. Total ascorbic acid (vitamin C) (mg 100 g^{-1}) content was determined in fruit samples harvested in the first, middle, and last harvest seasons and stored in deep-freeze at –20 °C. Spectrophotometric readings were performed at 520 nm. Vitamin C values obtained from the three different harvests were averaged.

During the experiment, runners were counted and removed, and the number of crowns of all plants in each plot was counted at the end of the intensive harvest period (Demirsoy et al., 2007). Plant biomass data (total plant dry weight) according to Demirsoy et al. (2012) was obtained from two plants harvested from every plot at the end of June 2015. Plants were dried at 70 °C in an oven. Total plant dry weight included root, crown, leaf, flower, and fruit dry weights.

2.4. Experimental design and statistical analyses

The experiment entailed four replications in a split-plot experimental design. From among the experimental variables, the production systems (open field and high tunnel) were taken as the main plots and the cultivars (nine cultivars) were randomly placed in the subplots. Experimental plots were 3.4 m long and included 20 plants. Analysis of variance to compare strawberry cultivars and production systems in terms of fruit yield, quality characteristics, and vegetative growth was performed using SPSS 17.0 (SPSS Inc., Chicago, IL, USA). Data means obtained from different measurements were separated using Duncan's multiple range test at the 1% and 5% significance levels. In the comparison of production systems, the pairwise comparison test (t-test) was applied using the same package program.

3. Results and discussion

3.1. Harvest period

The earliest cultivars were Fortuna (May 6) and Rubygem and Festival (May 8) in open field conditions and Fortuna, Festival, San Andreas, Albion, and Monterey (1 April) and Rubygem and Camarosa (8 April) in the high tunnels. Sweet Ann was the latest variety under both growing condition (May 24 in the open field and April 20 in the high tunnels). Previous studies confirmed that Sweet Ann is a late variety (Soysal et al., 2019). The fruit harvest started about 1 month earlier in the high tunnels due to the higher air and soil temperatures in the period from the closing of the covers to the harvest (Figures 1 and 2). Paranjpe et al. (2003) indicated that warmer air temperatures can be maintained inside protective structures during winter with higher early-season strawberry yields than in open fields. Previous studies also revealed that earliness progresses under protective structures (Öztürk and Demirsoy, 2004; Kadir et al., 2006; Gündüz and Özdemir, 2008; Crespo, 2009; Rowley et al., 2010; Salamé-Donoso et al., 2010; Gündüz and Özdemir, 2012). The harvest period took from 16 weeks (Monterey, Amiga, Fortuna, Rubygem) to 21 weeks (Albion) in the open field, ending on October 5. The harvest period took slightly longer in the high tunnels than the open field, ranging from 20 weeks (Sweet Ann) to 22 weeks (Monterey, Albion, San Andreas, Festival) and ending on September 1 for all cultivars.

In the open field, the harvest period took about 16–18 weeks for SD cultivars (16 for Rubygem, Fortuna, and Amiga; 17 for Camarosa; 18 for Festival) and 16–21 weeks for DN cultivars (16 for Monterey, 19 for Sweet Ann, 20 for San Andreas, and 21 for Albion). Contrary to the short harvest periods of 4–6 weeks reported for short-day cultivars,[2] SD cultivars tested in our study conditions had long harvest periods similar to those of the DN cultivars. We attribute this to the cool summer conditions in northern Türkiye, with average summer temperatures ranging from 21.1 °C in June to 24.4 °C in August in the open field (Figure 1), which supported reblooming not only in DN cultivars but also in SD cultivars. Taylor (2002) reported that in a short-day environment, flower bud initiation in the SD type occurs continuously between 10 °C and 25 °C. The harvest periods of the DN cultivars were 3 weeks longer than those of the SD cultivars. This crop coinciding with the autumn season is valuable due to high prices.

3.2. Yield (total, marketable, and percent marketable yield)

The high tunnels did not affect any yield-related parameters (Table 1). Contrary to our results, previous studies (Kadir et al., 2006; Salamé-Donoso et al., 2010; Medina et al., 2011; Rowley et al., 2011; Lewers et al., 2017) reported that protected structures increased overall and marketable yields compared to open fields. Similarly, Orde and Sideman (2019) determined that protected cultivation in a low tunnel did not affect the total yield. Grijibaldi et al. (2015) reported that while a high tunnel system provided yield increase and decreased the losses in the Monterey cultivar, it reduced fruit losses in the Albion cultivar, but it did not differ in yield compared to plants grown in an open field. In our experiment, the yields under the high tunnels were relatively low compared to the open field. The early-blooming flowers at the end of January under high tunnel conditions were collected considering the possibility of them not fruiting due to low temperatures and dead flowers were counted. According

2 Orde K, Sideman B, Pritts M, Demchak K (2018). Low Tunnel Strawberry Production Guide [online]. Website https://extension.unh.edu/sites/default/files/migrated_unmanaged_files/Resource007429_Rep10703.pdf [accessed 10 March 2023].

to the calculations based on the average fruit weight and number of flowers, the product loss experienced per plant was 65.5 g for Camarosa, 77.7 g for Festival, 307.5 g for Fortuna, 118.3 g for Rubygem, 40.8 g for Amiga, 15.8 g for Sweet Ann, 85.1 g for San Andreas, 80.6 g for Monterey, and 129.2 g for Albion (Table 1). This is a possible reason for the relatively lower yields in the high tunnels.

Cultivar significantly affected all yield parameters (Table 1). Monterey produced the highest total and marketable yield, respectively followed by Fortuna, Rubygem, Sweet Ann, and Albion. The total yield per plant of these cultivars was between 721.3 g (Albion) and 946.4 g (Monterey), while marketable yield per plant was between 611.7 g (Albion) and 819.6 g (Monterey). Yield performances of these cultivars in our trial were higher than reported in previous studies with values of 307.8–497.8 g $plant^{-1}$ for Monterey, 283.7–629.8 g $plant^{-1}$ for Albion, and 220.5–514.5 g $plant^{-1}$ for Sweet Ann (Ruan et al., 2013b; Özbahçali and Aslantaş, 2015; Gu et al., 2017; Geçer et al., 2018; Gude et al., 2018a, 2018b; Çolak et al., 2019; Orde and Sideman, 2019; Rana and Gu, 2020). Thus, the Monterey, Fortuna, Rubygem, Sweet Ann, and Albion cultivars stood out as exceptional cultivars in relation to fruit production. On the other hand, Festival, Camarosa, and Amiga constantly produced the lowest total and marketable yields in this study.

The highest percent marketable yield was obtained from Monterey (86.3%), followed by Albion (84.8%) and Fortuna (84.4%). Gude et al. (2018a, 2018b) also obtained the highest marketability from Monterey (82.2%–85.0%) and Albion (83.0%–89.0%). The lowest percent marketable yield was obtained from Camarosa followed by Rubygem and Sweet Ann (Table 1) due to the high amount of misshapen and damaged fruits in these cultivars, as Kandemir et al. (2019) similarly reported.

The Monterey cultivar had significantly greater total yield (Figure 4) and marketable yield (Figure 5) under open field conditions, producing 362.2 g $plant^{-1}$ total yield and 287 g $plant^{-1}$ marketable yield more under open field conditions compared to high tunnel conditions. Thus, the Monterey × open field combination was the best, followed by Sweet Ann and Rubygem under open field conditions, in terms of total fruit production (Figure 4) and followed by only Sweet Ann under open field conditions in terms of marketable fruit production (Figure 5). These results show that DN cultivars perform better in open fields compared to high tunnels. This was observed for the total and marketable yields of all DN cultivars studied (Figures 4 and 5). The low yields of the DN cultivars under high tunnel conditions were probably due to poor temperature control. In Figure 1, it is seen that the temperatures in the high tunnels were higher than those in the open field between May and mid-July. Especially in June, July, and August, the average maximum temperatures were respectively 30.1, 33.5 and 31.5 °C in the open field and 38.1, 35.8, and 36.4 °C in the high tunnels. In addition, daily extreme temperatures between 40.5 and 47.5 °C for 11 days in June were recorded in the high tunnels before the shadow cover was in place on June 25. Leblanc (1988) noted that very high temperatures hindered the development of fruits and reduced the growth and biomass of DN strawberries. The Camarosa and Festival × open field combinations produced the lowest total (Figure 4) and marketable (Figure 5) fruit production levels. Looking at the marketable yield percentage of the total, Monterey

Table 1. Effects of production systems and cultivars on total, marketable, and percent marketable yield.

	Yield (g $plant^{-1}$)	Marketable yield (g $plant^{-1}$)	Marketable yield (total %)
Production systems			
High tunnel	730.9	606.5	82.8
Open field	781.9	637.2	80.9
P (production systems)	NS	NS	NS
Cultivars			
Amiga	648.6 b	541.2 b	83.4 abc
Fortuna	835.6 ab	708.5 ab	84.4 ab
Rubygem	844.3 ab	655.6 ab	77.9 cd
Festival	605.6 b	494.9 b	81.2 a-d
Camarosa	638.3 b	494.6 b	76.6 d
Sweet Ann	884.1 ab	712.1 ab	79.9 bcd
Monterey	946.4 a	819.6 a	86.3 a
San Andreas	683.6 ab	558.9 b	82.3 a–d
Albion	721.3 ab	611.7 ab	84.8 ab
P (cultivars)	<0.01*	<0.01*	<0.01*
P (production system × cultivar)	<0.01*	<0.01*	<0.01*

P: Probability; NS: nonsignificant; *: means followed by the same letter in the same column or line are not significantly different.

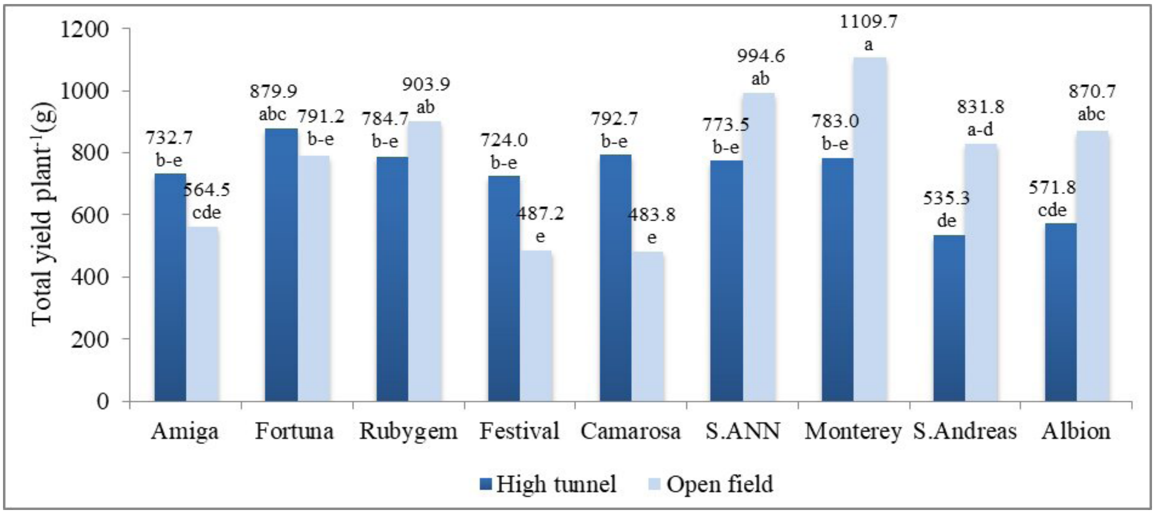

Figure 4. Effects of production systems and strawberry cultivars on total yield.

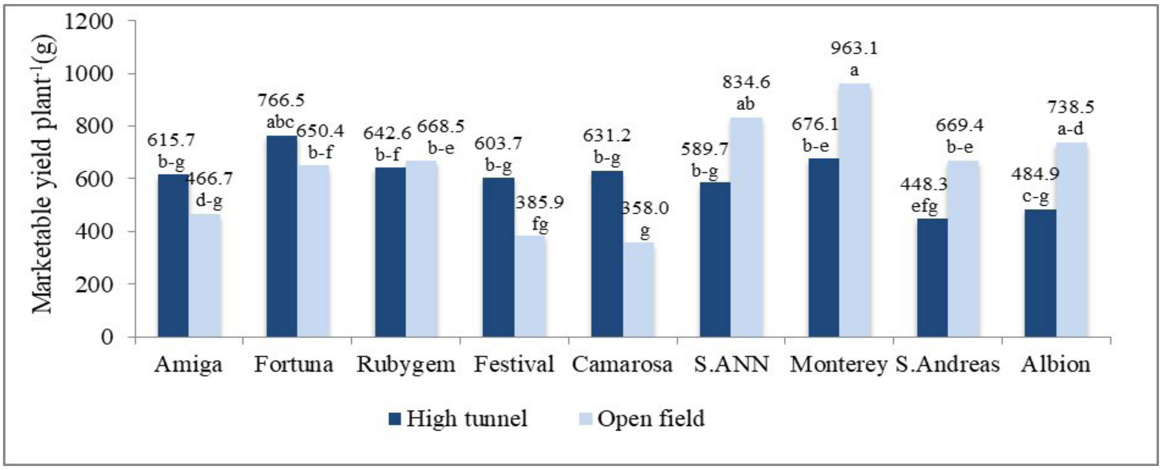

Figure 5. Effects of production systems and strawberry cultivars on marketable yield.

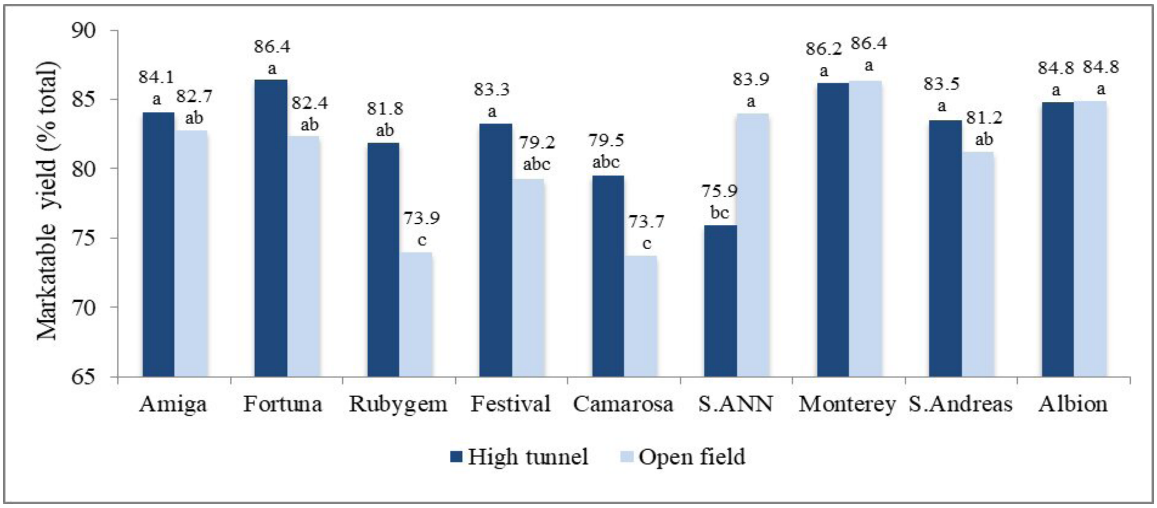

Figure 6. Effects of production systems and strawberry cultivars on percent marketable yield.

and Albion under both production conditions and Amiga, Fortuna, Festival, and San Andreas under high tunnel conditions were the best combinations (Figure 6).

3.3. Fruit quality (fruit weight, SSC, TAC, vitamin C, and fruit firmness)

All fruit quality parameters were affected by production system, cultivar (except vitamin C), and production system × cultivar interactions (Table 2).

Average fruit weight was significantly greater under high tunnel conditions with a value of 14.2 g compared to the open field (11.7 g) (Table 2), which corresponds to an increase of about 21%. In previous studies, it was found that the effect of low tunnels on fruit weight changed depending on the location, year, and variety (Petran, 2016; Orde and Sideman, 2019), while high tunnels were shown to increase fruit weight, similarly to our study (Kadir et al., 2006; Medina et al., 2011). DN cultivars Sweet Ann, Albion, and Monterey produced the largest fruits (15.1, 13.9, and 13.8 g, respectively), while Festival had the smallest (10.8 g) (Table 2). In previous studies, fruit sizes of the same DN cultivars varied between 7.41 and 18.25 g depending on the location, year, and management practices (Ruan et al., 2013b; Petran, 2016; Gude et al., 2018a, 2018b; Orde and Sideman, 2019). Compared to other studies, the fruit sizes of DN cultivars in our experiment were acceptable. On the other hand, evaluating the performance of different strawberry cultivars managed organically under high tunnel conditions, Gu et al. (2017) determined that the fruit

Table 2. Effects of production systems and cultivars on fruit characteristics.

	Fruit weight (g)	SSC (%)	Titratable acidity (%)	Vitamin C (mg 100 g^{-1})	Fruit firmness (kg cm^{-2})
Production systems					
High tunnel	14.2 a	6.3 a	0.66 a	18.9 a	0.48 a
Open field	11.7 b	5.9 b	0.63 b	14.1 b	0.42 b
P (production systems)	<0.01*	<0.05*	<0.05*	<0.01*	<0.01*
Cultivars					
Amiga	11.5 bc	5.5 d	0.58 de	13.7	0.54 a
Fortuna	13.5 ab	5.6 cd	0.54 e	19.5	0.48 ab
Rubygem	13.4 ab	6.6 ab	0.59 de	15.6	0.45 b
Festival	10.8 c	6.5 ab	0.63 cd	22.3	0.41 b
Camarosa	11.4 bc	5.9 bcd	0.70 ab	14.6	0.44 b
Sweet Ann	15.1 a	5.9 bcd	0.68 bc	12.8	0.46 b
Monterey	13.8 a	6.2 abc	0.61 cde	18.1	0.41 b
San Andreas	13.3 ab	5.9 bcd	0.74 ab	16.8	0.42 b
Albion	13.9 a	6.7 a	0.76 a	15.5	0.45 b
P (cultivars)	<0.01*	<0.01*	<0.01*	NS	<0.01*
P (production system × cultivar)	<0.01*	<0.01*	<0.01*	<0.01*	<0.01*

P: Probability; NS: nonsignificant; *: means followed by the same letter in the same column or line are not significantly different.

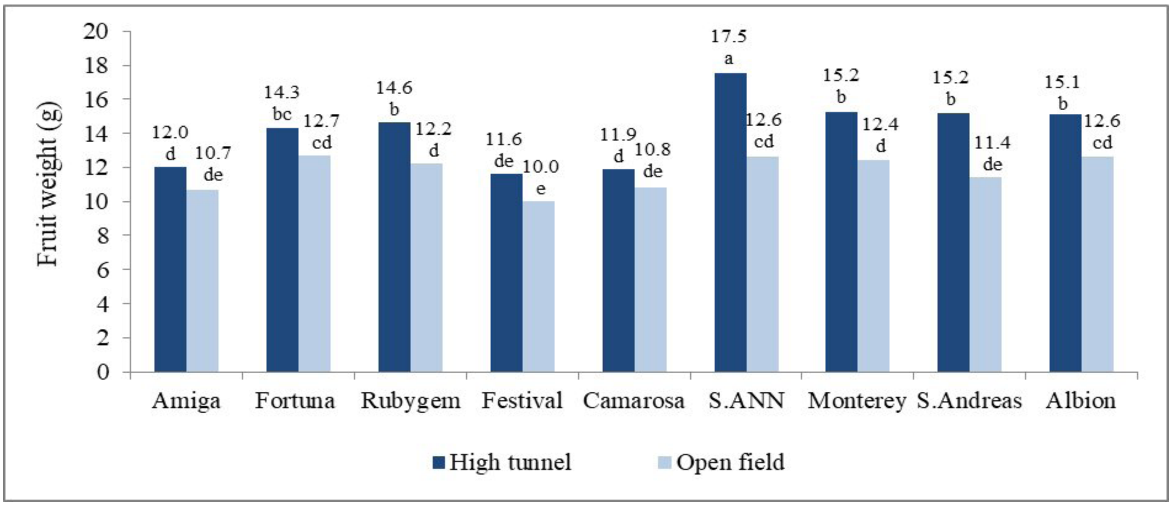

Figure 7. Effects of production systems and strawberry cultivars on fruit weight.

weight of the Festival cultivar varied from 36.9 g and 8.2 g between January and May. According to Figure 7 showing production system × cultivar interactions, DN cultivars Sweet Ann (17.5 g), Monterey (15.2 g), San Andreas (15.2 g), and Albion (15.1 g) respectively produced larger fruits under high tunnel conditions than in the open field (respectively 12.6, 12.4, 11.4, and 12.6 g for the latter). SD cultivar Rubygem under high tunnel conditions followed them. Orde and Sideman (2019) reported that San Andreas and Sweet Ann among the cultivars studied produced the largest fruits in low tunnels, which supports our results.

SSC and TAC are very important characteristics in determining fruit quality. The values of SSC and TAC were significantly higher under high tunnel conditions than in the open field in the present study (Table 2). This is consistent with experimental findings that protected conditions increase SSC and TAC (Kadir et al., 2006; Voča et al., 2006; Salamé-Donoso et al., 2010; Qureshi et al., 2012; Orde and Sideman, 2019). SSC and TAC differed significantly between cultivars. The highest SSC was obtained from Albion (6.7%), followed by Rubygem (6.6%) and Festival (6.5%), while the lowest was obtained from Amiga (5.5%), followed by Fortuna (5.6%) (Table 2). Higher SSC values for Albion were also confirmed by some other researchers (Ruan et al., 2013a; Laugale et al., 2014; Petran, 2016; Oğuz et al., 2017; Orde and Sideman, 2019; Rana and Gu, 2020; Gude et al., 2021). Similar to SSC, Albion (0.76%) was the cultivar with the highest TAC content and Fortuna (0.54%) had the lowest (Table 2). High acid contents for Albion (Oğuz et al., 2017) and low acid contents for Fortuna (Serçe et al., 2012) were also reported in previous studies. Significant system × cultivar interactions for SSC and TAC were noticed (Table 2). Albion under open field conditions (6.8%) and Festival under high tunnel conditions (6.8%) had higher SSC values, while Amiga and Fortuna under open field conditions had the lowest (5.3% and 5.4%, respectively) (Figure 8). Albion × high tunnel followed by Camarosa

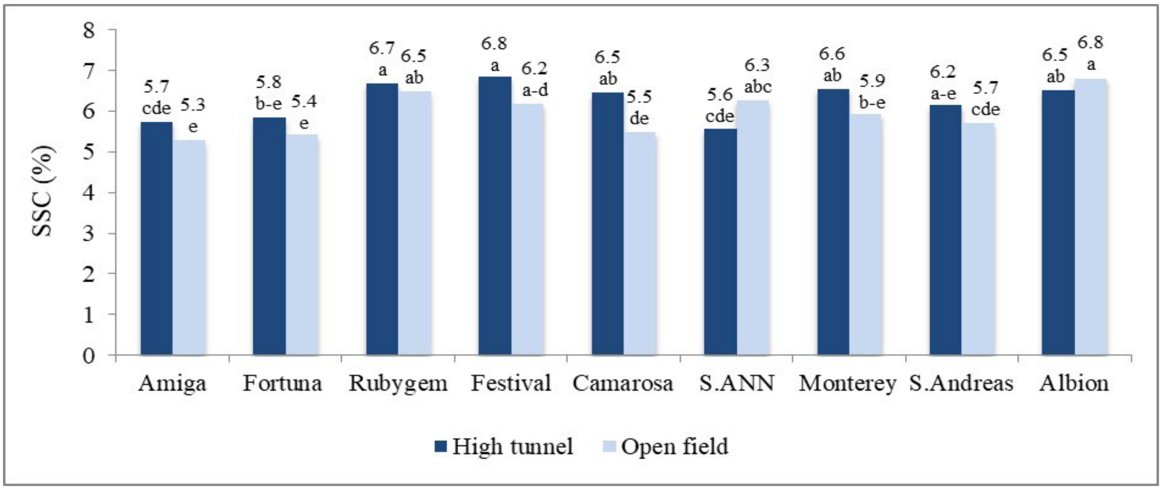

Figure 8. Effects of production systems and strawberry cultivars on soluble solid contents.

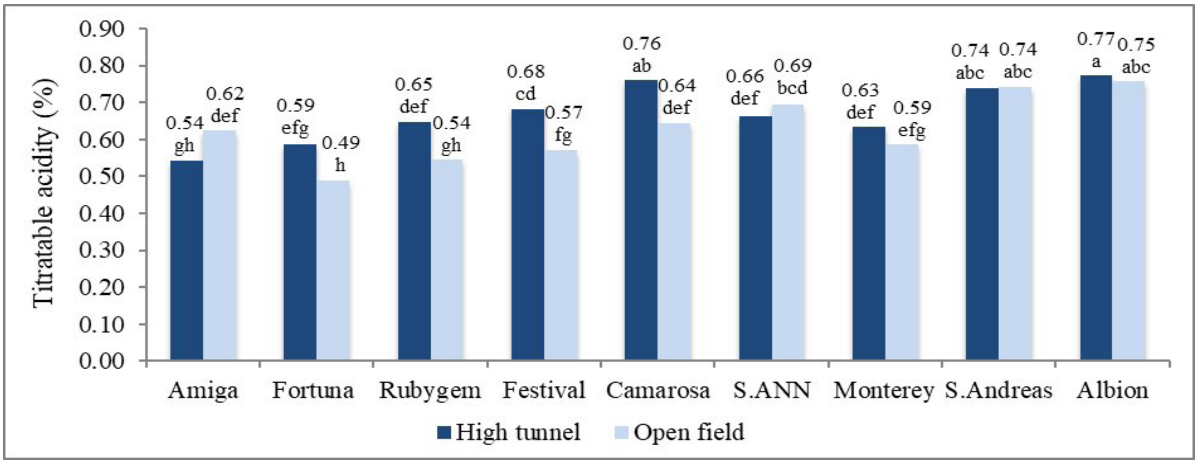

Figure 9. Effects of production systems and strawberry cultivars on titratable acid contents.

× high tunnel had the highest TAC (0.77% and 0.76%, respectively), while Fortuna × open field (0.49%) had the lowest (Figure 9). This indicates that SSC and TAC in strawberries are significantly affected by genotype and environmental influences (Shaw, 1990; Voča et al., 2006; Voča et al., 2008; Salamé-Donoso et al., 2010; Ruan et al., 2013a; Petran, 2016). The SSC contents in our experiment were relatively low. This can be explained by the fact that the weather was cloudy almost until June, the lighting was insufficient (Figure 3), and the average temperatures were relatively low in April (16.1 °C for the high tunnels, 9.9 °C for the open field) and May (20.5 °C for the high tunnels, 16.2 °C for the open field) (Figure 1), which is the intensive harvest period.

Vitamin C levels were significantly higher under high tunnel conditions at 18.9 mg 100 g^{-1} compared to the open field (14.1 mg 100 g^{-1}), but no significant difference was observed between the cultivars (Table 2). Cultivar × production system interactions were significant. Festival followed by Fortuna were the cultivars with significantly high vitamin C levels under high tunnel conditions (Table 2; Figure 10). The lowest vitamin C contents were observed in Festival and Amiga in the open field, Camarosa under high tunnel conditions, and Sweet Ann in both production systems (Figure 10). These results agree with earlier reports that high tunnel conditions produced higher vitamin C levels compared to open fields (Voča et al., 2006). In our study, vitamin C values were found to be lower than those reported in previous studies (Özdemir, 2003; Crespo et al., 2009; Wan et al., 2014). This can be explained by variety and ecology differences.

Fruit firmness was significantly higher in fruits grown under tunnel conditions (0.48 kg cm^{-2}) compared to the open field (0.42 kg cm^{-2}). Fruit firmness showed significant differences among cultivars. While Amiga showed the highest fruit firmness, followed by Fortuna (0.54 and 0.48 kg cm^{-2}, respectively), all other cultivars had similar fruit firmness (Table 2). Soria et al. (2008) reported that Amiga has extremely hard fleshy fruits. Serçe et al. (2012) reported that the fruit firmness of 7 examined strawberry cultivars were similar to each other, although Festival had lower and Amiga had higher fruit firmness values. Amiga and Sweet Ann showed the highest fruit firmness in the high tunnels in the present study, while Fortuna showed the highest fruit firmness in the open field (Figure 11). This indicates that the firmness of the fruit flesh can be affected by the conditions of the growing place. Environmental conditions during fruit development affect fruit flesh firmness in strawberries (Burkhart, 1943). Serçe et al. (2008) also stated that the fruit firmness of the same genotype differs in different growing places.

3.4. Vegetative growth (crown and runner numbers, plant biomass)

The growth parameters examined in this study were affected by production system, cultivar, and production system × cultivar interactions (Table 3).

Numbers of crowns in strawberry plants grown in the open field (5.9) were significantly higher than those of the high tunnels (3.9) (Table 3). Amiga had the highest number of crowns (6.1), while Albion had the lowest (3.6). Weak vegetative growth including the smallest number of branch crowns and smaller canopy size was also detected in previous studies for Albion (Gu et al., 2017; Soysal et al., 2019). Amiga (7.2) under open field conditions produced the highest number of crowns, while Albion (2.8) followed by San Andreas, Monterey, and Festival produced the lowest under high tunnel conditions (Table 3). It was notable that all DN cultivars generally had the lowest crown numbers under high tunnel conditions. The DN cultivars produced 30.4% fewer branch crowns than SD

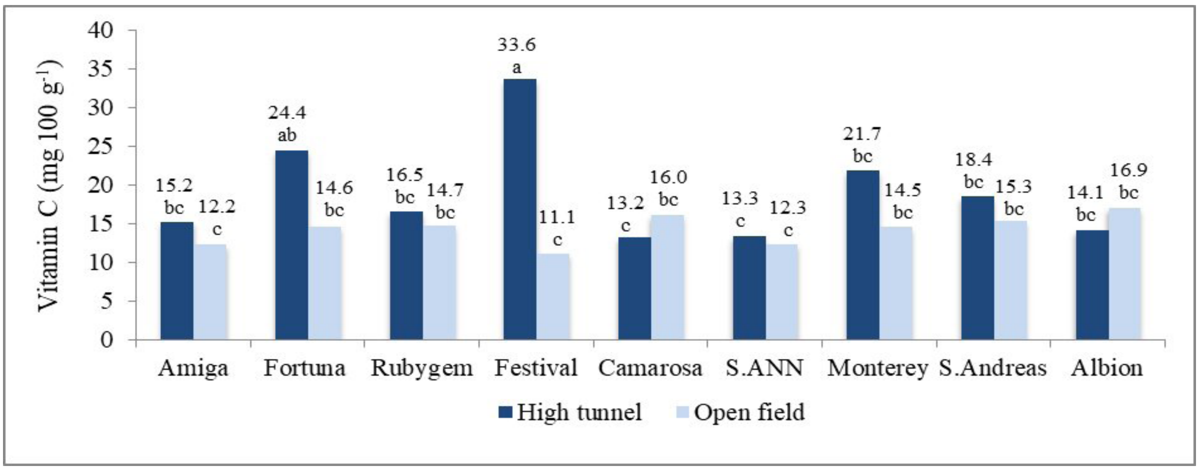

Figure 10. Effects of production systems and strawberry cultivars on vitamin C contents.

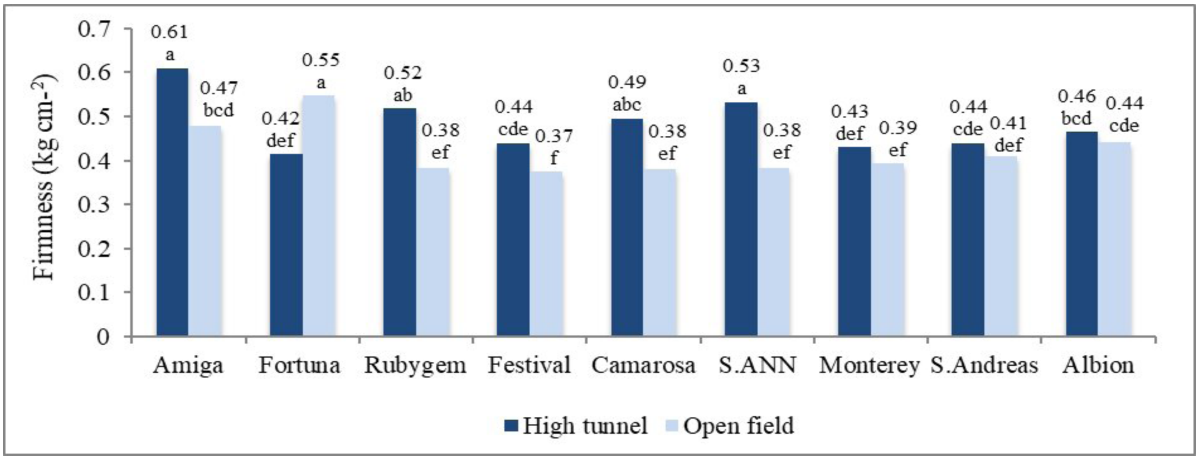

Figure 11. Effects of production systems and strawberry cultivars on fruit firmness.

Table 3. Effects of production systems and cultivars on crown numbers, runner numbers, and total plant dry weight.

	Crown (no. plant^{-1})	Runner (no. plant^{-1})	TPDW (g plant^{-1})
Production systems			
High tunnel	3.9 b	15.7 b	81.4 b
Open field	5.9 a	23.9 a	128.9 a
P (production systems)	<0.01*	<0.01*	<0.01*
Cultivars			
Amiga	6.1 a	21.5 bc	115.6 ab
Fortuna	5.2 ab	30.4 ab	119.6 ab
Rubygem	5.5 ab	20.9 bc	102.5 ab
Festival	4.7 ab	33.4 a	142.7 a
Camarosa	5.2 ab	14.8 c	114.7 ab
Sweet Ann	5.3 ab	15.0 c	94.4 ab
Monterey	4.1 ab	13.4 c	101.9 ab
San Andreas	4.9 ab	11.8 c	83.3 b
Albion	3.6 b	17.1 c	72.0 b
P (cultivars)	<0.05*	<0.01*	<0.01*
System × cultivar			
Amiga (HT)	5.1 b–e	13.5 def	81.1 def
Fortuna (HT)	4.2 c–f	30.6 b	88.5 c–f
Rubygem (HT)	4.9 b–f	18.1 cde	86.6 c–f
Festival (HT)	3.5 ef	16.8 c–f	124.7 a–d
Camarosa (HT)	4.2 c–f	8.8 f	85.6 c-f

Table 3. Continued

Sweet Ann (HT)	4.1 def	11.1 ef	77.2 def
Monterey (HT)	3.5 ef	14.4 def	70.9 ef
San Andreas (HT)	3.6 ef	10.9 ef	68.8 ef
Albion (HT)	2.8 f	17.9 cde	49.2 f
Amiga (OF)	7.2 a	29.6 b	150.2 a
Fortuna (OF)	6.2 a–d	30.5 b	88.5 c–f
Rubygem (OF)	6.2 a–d	23.7 bc	118.5 a–e
Festival (OF)	6.0 a–d	50.1 a	160.6 a
Camarosa (OF)	6.3 abc	20.7 cd	143.7 ab
Sweet Ann (OF)	6.6 ab	18.9 cde	111.6 a–e
Monterey (OF)	4.8 b–f	12.5 ef	132.8 abc
San Andreas (OF)	6.3 abc	12.8 def	97.8 b–f
Albion (OF)	4.5 b–f	16.3 c–f	97.8 b–f
P (production system × cultivar)	<0.01*	<0.01*	<0.01*

P: Probability; NS: nonsignificant; HT: high tunnel; OF: open field; *: means followed by the same letter in the same column or line are not significantly different.

cultivars in the open field, while they produced 36% fewer in high tunnel conditions. The plants grown in the open field produced more runners (23.9) compared to plants grown under high tunnel conditions (15.7) (Table 3). This finding of 34.3% less runner formation in high tunnels than open field conditions in our study were similar to results showing a reduction in runner initiation under protected structures (Kadir et al., 2006; Orde and Sideman, 2019). This reduction was significant for the Amiga, Rubygem, Festival, Camarosa, Sweet Ann, and San Andreas cultivars; the reduction in the number of runners under high tunnel conditions varied from 66% in Festival to 14.8% in San Andreas. The SD cultivars except Camarosa had the highest numbers of runners, and particularly Festival, while all DN cultivars had lower numbers of runners (Table 3). On the other hand, it was remarkable that the total number of runners of the DN cultivars was 52.6% less than that of the SD cultivars. Lower runner yield was previously reported for DN cultivars (Sonsteby and Heide, 2007). There was significant production system × cultivar interaction, with the Festival × open field combination producing the highest number of runners while Monterey × open field and Camarosa, Sweet Ann, and San Andreas × high tunnel produced the least (Table 3). This finding for the Festival and Monterey cultivars may explain the low productivity of Festival and the high productivity of Monterey in the open field (Figure 4), as a negative relationship was previously reported between the number of runners and yield (Manakasem and Goodwin, 2001). Handley et al. (2009) stated that runners are sinks that reduce the resources that could support flower and fruit production.

The total plant dry weights (TPDWs) of the plants grown in the open field (128.9 g plant^{-1}) were significantly higher than those of plants grown under high tunnel conditions (81.4 g plant^{-1}) (Table 3). Festival (142.7 g plant^{-1}) had the highest TPDW, while DN cultivars San Andreas (83.3 g plant^{-1}) and Albion (72.0 g plant^{-1}) had the lowest. Significant production system × cultivar interactions were detected, as Festival and Amiga under open field conditions had the highest TPDWs and DN cultivars Albion, San Andreas, and Monterey under high tunnel conditions respectively had the lowest TPDWs (Table 3).

Overall, the data on growth parameters showed that plant growth was higher in the open field. These results contradict previous reports that larger and more leaves, more branch crowns, and greater plant biomass were obtained under protected structures and therefore the protected structures promoted growth compared to open field conditions (Kadir et al., 2006). Salamé-Donoso et al. (2010) attributed the wider plant canopy obtained under high tunnels to etiolation due to decreased PAR in the greenhouse. The relatively higher yields and greater plant growth in the open field in our study can be explained by the relatively cooler spring and summer temperatures in the open field.

4. Conclusion

In general, total, marketable, and percent marketable yields were sufficient in both production systems in our study and there were no significant differences between the growing sites. Lower levels of plant growth were obtained in the high tunnels than in the open field. This was probably due to high temperatures and insufficient lightning under the tunnels. However, the lower plant growth under the high tunnels did not cause a significant decrease in yield. In our study region, which is located in the north of Türkiye, lightning is low due to the cloudy weather at the beginning of spring. In addition, the tunnel cover also reduced the light (Figure 3). This situation can have negative effects on flowering, fruit set, and plant growth. For this reason, it is essential to use tunnel covers with high light transmittance in this region. In our study, the tunnels positively affected fruit quality. Despite its low productivity, especially in the tunnels, Albion stood out in terms of many fruit quality parameters.

Overall, all cultivars showed superior performance in terms of yield parameters; the total and marketable yields of all cultivars were above 500 g plant^{-1}, both in the open field (except Festival and Camarosa) and in the high tunnels. However, production system × cultivar interactions showed that cultivar selection was important for both production systems. In general, the total and marketable yields of all DN cultivars were higher in the open field than in the high tunnels. This was probably due to poor temperature control in the high tunnels. In the open field, the Monterey, Sweet Ann, and Albion DN cultivars performed particularly well in all yield parameters and their total yields ranged from 870.7 to 1109.7 g plant^{-1}. SD cultivar Rubygem also had high total yield; however, a high rate of misshapen fruit in Rubygem and misshapen and damaged fruit in Sweet Ann were detected. In the high tunnels, the Fortuna, Rubygem, Festival, and Amiga SD cultivars and Monterey DN cultivar showed superior performance in all yield parameters, with total yields ranging from 724.0 to 879.9 g plant^{-1}. Despite their high productivity in the high tunnels, rates of misshapen fruit formation in Camarosa and misshapen and damaged fruit formation in Sweet Ann were high; they were the only two cultivars having lower marketability. Rubygem had a high tendency to produce misshapen fruit in the high tunnels, as well. Data on misshapen and damaged fruit formation in open field and tunnel conditions were reported in our previous study for all of these strawberry cultivars (Kandemir et al., 2019).

Average total yields and marketable yields were respectively 714.5 and 579.0 g plant^{-1} for SD cultivars and 808.9 and 675.6 g plant^{-1} for DN cultivars. Finally, DN cultivars can be characterized by high productivity and a long harvest season (16–21 weeks) in northern Türkiye, where summer temperatures are moderate. It is noteworthy that the SD cultivars also had a long harvest season (16–18 weeks) in this area.

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