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EFFECT OF NUTRIENT SOLUTION CONCENTRATION ON GROWTH, YIELD, AND FRUIT QUALITY OF TOMATO GROWN HYDROPONICALLY IN SINGLE-TRUSS PRODUCTION SYSTEM

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ABSTRACT

The single-truss production system for tomatoes (*Solanum lycopersicum* L.) is a relatively new developed cultivation technology that guarantees high yields and high-quality fruit throughout the annual cycle. In this study, we examined the impact of electrical conductivity (EC) of nutrient solutions on the growth, yield, and fruit quality of tomatoes grown in a single-truss system in a hydroponic culture. Plants were supplied with nutrient solution at the following EC values: 0.8, 1.0, 1.2, and 1.4 mS·cm^{-1} in the spring and summer cycles, and at 1.0, 1.2, 1.4, and 1.6 mS·cm^{-1} in the winter cycle. In the spring cycle, the EC of the nutrient solution increased in all treatments, particularly after pinching the main stem. Increased EC values of nutrient solutions were also recorded at the 1.2 and 1.4 EC in the summer cycle and the 1.4 and 1.6 EC in the winter cycle. The leaf number per plant did not differ between treatments in all production cycles. The largest leaf area was found at the 1.2 and 1.4 EC in the spring cycle and the 1.0 and 1.2 EC during the summer. During the winter cycle, no differences in leaf area between treatments were observed. In spring, plants at the 1.2 and 1.4 EC had the highest yields and largest fruits, while during the summer, plants at the 1.0 and 1.2 EC produced the most fruit. In winter, the highest yield was found at the 1.4 EC. The soluble solids concentration (SSC) of fruit was increased at the 1.4 EC both in the spring and summer cycles, while in the winter cycle, there was no difference between the treatments. Only fruit at the 1.4 EC in the summer cycle had an increased acidity. The findings indicate that under greenhouse conditions, tomato cultivation in a single-truss system can be successful if the plants are supplied with a nutrient solution at an EC value of 1.2–1.4 mS·cm^{-1}.

Key words: growth, nutrient solution concentration, quality, tomato, yield

INTRODUCTION

Tomato (*Solanum lycopersicum* L.) is one of the world's most well-known crops consumed fresh and processed. Recently, fresh consumption, the daily requirement for high-quality products, and tomato production have been increasing due to their several health benefits, such as anticancer quality, decreased risk of cardiovascular and gastrointestinal illnesses, neurological benefits, improvement in skin, exercise recovery, and immune responses (Jones 2007; Collins et al. 2022). In 2020, the world production of tomato fruit was 184.7 million tons (FAO 2020). Conventionally, tomatoes are grown in a multi-truss system in which the fruits are harvested until the sixth or seventh clusters. However, a new technique for growing tomato plants as a single-truss production system has been developed.

In this system, plants are trained to pinch the main stem and maintain a few leaves over the first cluster, and only one cluster is harvested (Giacomelli et al. 1994; Okano et al. 2001). According to those authors, the proposed system is intended

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to produce tomatoes with the highest yields and optimum fruit quality and maintain labor efficiency in training, pruning, and harvesting. Additionally, it allows for the implementation of a fast production cycle, multiple cropping throughout the year, automation capabilities, and the use of moving benches to increase output per unit area (Lu et al. 2012). Moreover, this production system reduces the risk of harm caused by high summer temperatures, which is common in conventional systems.

Numerous factors, such as insufficient light, air humidity, and high and low temperatures during summer and winter seasons, can adversely affect the growth and fruit yields of tomatoes grown at high densities (Holder & Cockshull 1990; Okano et al. 2001; Tewolde et al. 2016).

Tomato cultivation in the single-truss production system requires adequate electrical conductivity (EC) of nutrient solutions. However, no recommendation for the optimal range of EC values has been reported for the single-truss production system. This issue is crucial because Zhang et al. (2016) demonstrated that, tomato fruit contained an increased soluble solids concentration (SSC) under salinity stress conditions, and plants had reduced both growth and fruit yields. According to Johkan et al. (2014), an increased sugar status in tomato fruit under moderate salinity stress can be obtained without a decrease in fruit yields and their marketable quality. In this study, we examined the effects of EC values of nutrient solutions on the growth, yield, and fruit quality of tomatoes grown in a hydroponic system and trained in a single-truss production system.

MATERIALS AND METHODS

Study site, plant material, and growth conditions

Experiments were conducted in 2015 and 2016 in a semi-controlled greenhouse at the Field Science Center of Ibaraki University, Japan. Tomato seeds of the 'Momotaro York' cultivar were sown in a 49-cell tray filled with a commercial peat substrate on March 17th and June 26th, 2015, for the spring and summer production cycles, respectively. The seeds were germinated at 28°C for three days. Subsequently, for nearly one month, they were kept in a greenhouse where the temperature was maintained at approximately 25°C. They were watered with tap water until planting. Seedlings were obtained from Suzuyo Shoji on December 18th for the winter production cycle. Seedlings were then planted in a closed hydroponic system 10 × 115 cm density on April 17th, July 24th, and December 24th for the spring, summer, and winter production cycles, respectively.

Plants were supplied with nutrient solutions at the following EC values: 0.8, 1.0, 1.2, and 1.4 $mS \cdot cm^{-1}$ in the spring and summer production cycles and 1.0, 1.2, 1.4, and 1.6 $mS \cdot cm^{-1}$ in the winter cycle. Such a wide choice of EC values of the nutrient solutions was necessary to determine the optimal range for this production system. The solutions used were prepared by a means of the stock solutions containing the following mineral fertilizers: OAT House 9 (P_2O_5–K_2O: 51–33) at a rate of 2.0 $kg \cdot 100\ L^{-1}$ of water for the spring and summer production cycles or 1.55 $kg \cdot 100\ L^{-1}$ of water for the winter cycle; OAT House 2 (N–CaO: 11–23) at a rate of 9.5 $kg \cdot 100\ L^{-1}$ of water; OAT House 3 (N–K_2O: 13–46) at a rate of 8.1 $kg \cdot 100\ L^{-1}$ of water; OAT House 5 (N–K_2O–MnO–B_2O_3–Fe–Cu–Zn–Mo: 6 – 9 – 2 – 2 – 5 . 7 – 0.04–0.08–0.043) at a rate of 0.5 $kg \cdot 100\ L^{-1}$ of water; and OAT House 6 (MgO: 16) at a rate of 5 $kg \cdot 100\ L^{-1}$ of water. A linear equation based on the measured EC values of the stock solutions was used to determine the initial solution concentrations for all EC treatments. Plants were fertigated for 10 minutes after every 30 minutes in the spring production cycle and after every 50 minutes in the summer and winter cycles. Regardless of the production cycle, the solution pH for all treatments was 6.3.

Tomatoes were trained opposite each other and twisted counterclockwise so that the flower clusters were left outside. The main stem was pinched 2 cm above the second leaf of the first flower cluster. The upper two leaves were also twisted counterclockwise to improve ventilation. Suckers were regularly removed, and fruits were thinned to four per cluster when their diameter reached approximately 40 mm. During the winter production cycle, greenhouse heaters were activated when air temperature dropped below 10°C. In each treatment, there were 220 plants.

Observations

The daily temperatures of rooting media and plant canopy, the EC and pH of the nutrient solutions, and the weather conditions outside the greenhouse were recorded. The daily mean temperatures of the canopy and rooting media were monitored using data loggers (DS1921G-F50-thermochronic iButton, KN laboratory, Osaka, Japan). Twelve data loggers were used, six placed near the upper part of the plant and six within the media channels, which recorded temperature every ten minutes. EC and pH measurements of the nutrient solutions were taken using a pH meter (HI98129, Combo Hanna, Romania).

Plant growth indices

A random sample of 10 plants was assessed for each treatment for growth indices. The following growth indices were determined: plant height, stem diameter, leaf number, leaf chlorophyll content, and nitrate content in petiole sap. These parameters were determined every week until harvest. The plant height was measured from the medium surface to the growing point by a ruler, the stem diameter was determined by caliper, and leaf chlorophyll content was estimated using a portable chlorophyll meter (SPAD-502 P1us; Konica Minolta, Japan) on the three youngest fully developed leaves. Nitrate in the sap of petioles was measured on the recently matured leaves using a Nitrate meter (LAQUAtwin B-743, Horiba, Tokyo). To calculate the number of leaves per plant, only leaves longer than 2.5 cm were counted. Leaf area was determined using four harvested plants twice a month for each treatment. Fresh leaves with petioles were photographed, and the obtained pictures were analyzed for surface area using image analysis software (ImageJ 1.48v, Wayne Rasban, National Institutes of Health, Bethesda, Maryland, USA).

Biomass production

Four plants were harvested twice a month for each treatment, to determine the dry weights of stems, leaves, clusters, and fruits. The dry weights of the plants were measured by drying them at 60°C in a forced-draft oven (FS-60P, T.G.K, Tokyo, Japan) until a constant weight was reached.

The marketable yield and fruit quality

For fruit production and analysis, four replications, each with 20 plants, were chosen for each treatment. Fruits were collected from each replication, and their total number was divided by the number of plants to determine the average number of fruits per plant. Similarly, the total fruit weight from each replication was divided by the number of plants to calculate the average weight per plant. To determine the average weight of an individual fruit, we divided the fruit weight per plant by the number of fruits per plant. Fruits were classified as regular and damaged. Damaged fruits were classified as cracked and affected by blossom end rot (BER). Titratable acidity (TA) and SSC were determined as fruit quality parameters using a saccharic acidity meter (Hybrid PAL-BX|ACID F5; Atago, Tokyo, Japan). These parameters were measured on eighteen randomly selected fruits per replicate three times during the harvest period (six fruits at the beginning, middle, and final harvest). The fruits were juiced in a juicer, and the obtained juice was filtered through a paper filter. The SSC was measured directly in the juice, whereas TA was measured by diluting the fruit juice by a ratio of 1 : 50 with deionized water. The results of TA were expressed as the percentage content of citric acid.

Nutrient uptake

The absorbed amounts of nitrogen (N), phosphorus (P), potassium (K), magnesium (Mg), and calcium (Ca) by plants were estimated by the consumed amount of stock solution and planting density.

Statistical analysis

In order to investigate the isolated effects of EC treatments on tomato growth, yield, and fruit quality in each production cycle, data were subjected to one-way ANOVA, and Tukey's HSD test was employed for multiple comparisons ($p = 0.05$) using IBM SPSS Statistics 23.

RESULTS

Temperature and EC values

In the spring production cycle, the daily mean plant canopy temperature remained stable, ranging between 18 and 28°C (Fig. 1A). During the summer, temperatures rose to over 30°C until the middle of August and then decreased during the flowering stage (Fig. 1B). In the winter production cycle, temperatures were below 15°C until March 16th and gradually increased until the end of the cycle (Fig. 1C).

In the spring production cycle, the EC of the nutrient solution rapidly increased at the 1.4 and 1.2 treatments and gradually increased at the 1.0 and 0.8 treatments after pinching the main stem (Fig. 2A). In this production cycle, the EC values reached 4.60, 2.72, 1.54, and 1.10 $mS \cdot cm^{-1}$ by the first harvest, and 5.10, 3.10, 1.59, and 1.02 $mS \cdot cm^{-1}$ by the third harvest for the 1.4, 1.2, 1.0, and 0.8 EC, respectively. In the summer cycle, until August 15th (two days before pinching the main stem) the EC values of solutions increased to 3.46 and 1.50 $mS \cdot cm^{-1}$ for the 1.4 and 1.2 treatments, respectively, and decreased to 0.51 and 0.34 $mS \cdot cm^{-1}$ for the 1.0 and 0.8 treatments, respectively (Fig. 2B). In winter, the EC of solutions at bud appearance (January 13) were 2.02, 1.81, 1.20, and 1.04 $mS \cdot cm^{-1}$ for the 1.6, 1.4, 1.2, and 1.0 treatments, respectively. Then, during the fruit development period (until March 15th), the EC of solutions of all treatments decreased to the range of 0.30–0.68 $mS \cdot cm^{-1}$ (Fig. 2C).

Plant growth indices

In the spring production cycle, the final height of plants at the 1.4 and 1.2 EC was greater than that of the others (Fig. 3A). In the summer cycle, the tallest plants were found at the 0.8 EC. In contrast, in winter, plant heights were comparable among the tested EC (Fig. 3B, C). During the spring production cycle, from the third week of transplanting until the end of the experiment, the greatest stem diameter was found on plants at the 1.4 EC (Fig. 4A). In this cycle, no significant differences in stem diameter were found between the 1.0 and 0.8 treatments. In the summer cycle, the final stem diameter did not differ between plants from the tested EC (Fig. 4B). In winter, at the pinching time, the greatest stem diameter was observed at the 1.2 EC (Fig. 4C).

Across all production cycles, the final leaf number per plant did not differ between the tested treatments. The leaf number per plant in the spring cycle was 9, whereas in the summer and winter, it was almost 11 (Fig. 5A, B, C).

In the spring production cycle, from May 8 to June 19, the SPAD values on plants at the 0.8 EC were the lowest (Fig. 6A). However, at the last time point of SPAD readings (June 26), they did not differ between the tested treatments. In the summer cycle, significant differences in SPAD values between treatments were observed just after the first week of transplanting (August 2) (Fig. 6B). In the final week of measurement (October 11), the SPAD values on plants at the 1.4 and 1.0 EC were higher than those at the 1.2 and 0.8 EC. In the winter cycle, on February 27th and March 18th, the SPAD readings on plants at the 1.0 EC were lower than those of the other treatments (Fig. 6C).

In the spring cycle, in most cases, petiole sap nitrate concentrations were comparable between the tested treatments (Fig. 7A). However, there was a tendency indicating that the plants at the 1.4 EC had increased nitrate concentrations. Throughout the summer cycle, plants at the 1.2 EC had more nitrates, while plants at the 0.8 EC contained less nitrate than the other treatments (Fig. 7B). In the winter cycle, at most time points, petiole sap nitrate concentrations were the greatest at the 1.4 EC and the lowest at the 1.0 EC (Fig. 7C). In the spring cycle, leaf area (LA) of plants at the 1.4 and 1.2 EC were larger than that of the other EC (Fig. 8A). In the summer, LA did not differ significantly between treatments, except on August 27th and September 12th, where it was larger at the 1.2 EC than at the 1.4 and 0.8 EC (Fig. 8B). In the winter, no significant differences in LA were found (Fig. 8C).

Biomass production

At most time points in the spring production cycle, total dry weight (TDW) did not differ between the tested treatments (Fig. 9A). In this cycle, plants at the 0.8 EC had the lowest TDW. During the summer, only on September 12th (the reproductive plant stage) was the TDW of plants at the 1.2 EC greater than that at the 1.4 and 0.8 EC (Fig. 9B). In the winter cycle, a significant difference in TDW was found only on March 17th (the reproductive stage), where this parameter was greater at the 1.2 EC compared to the 1.0 and 1.6 treatments (Fig. 9C).

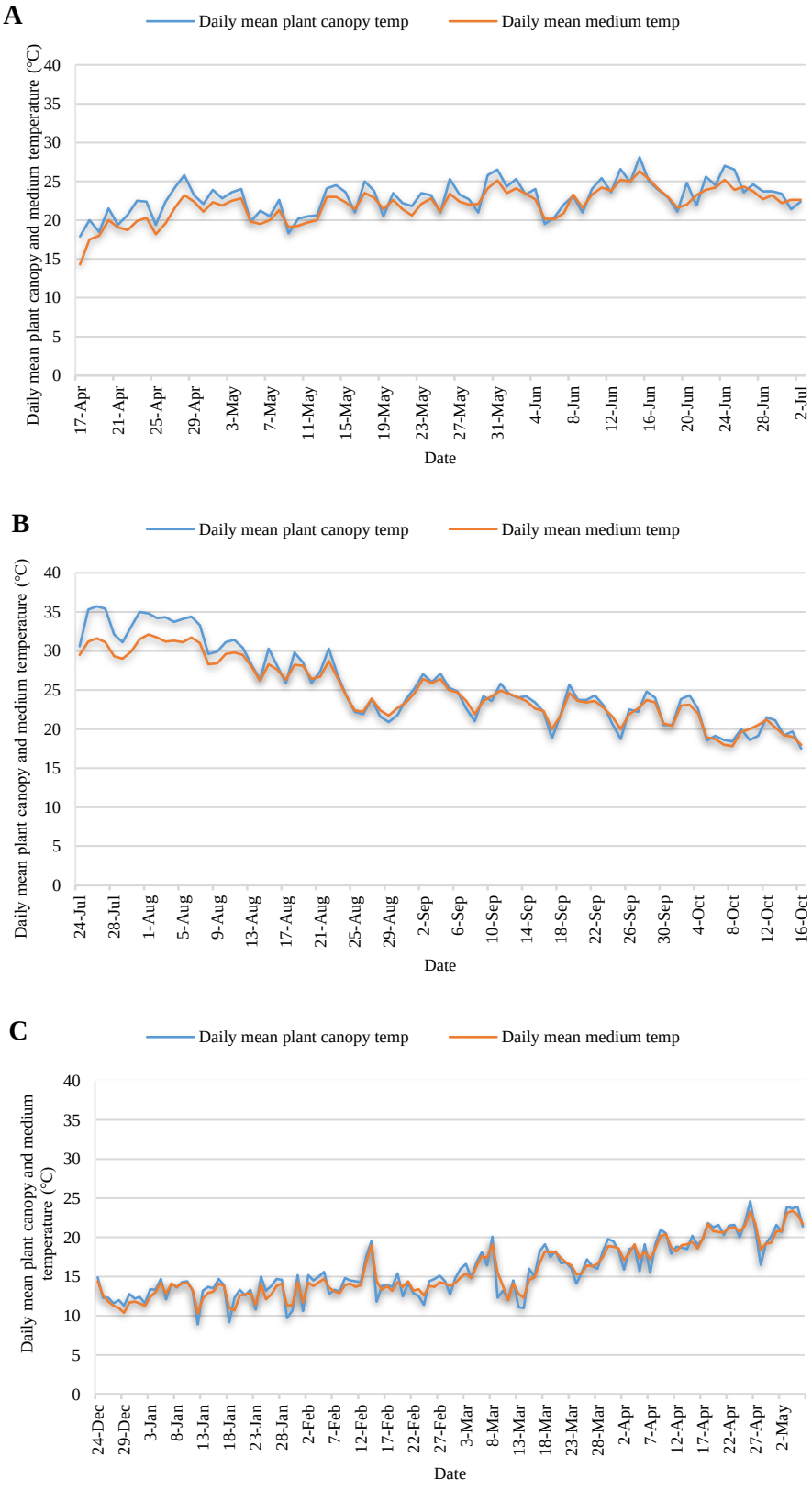


Figure 1. Daily mean temperatures of plant canopy and medium during the spring (A), summer (B), and winter (C) production tomato cycles

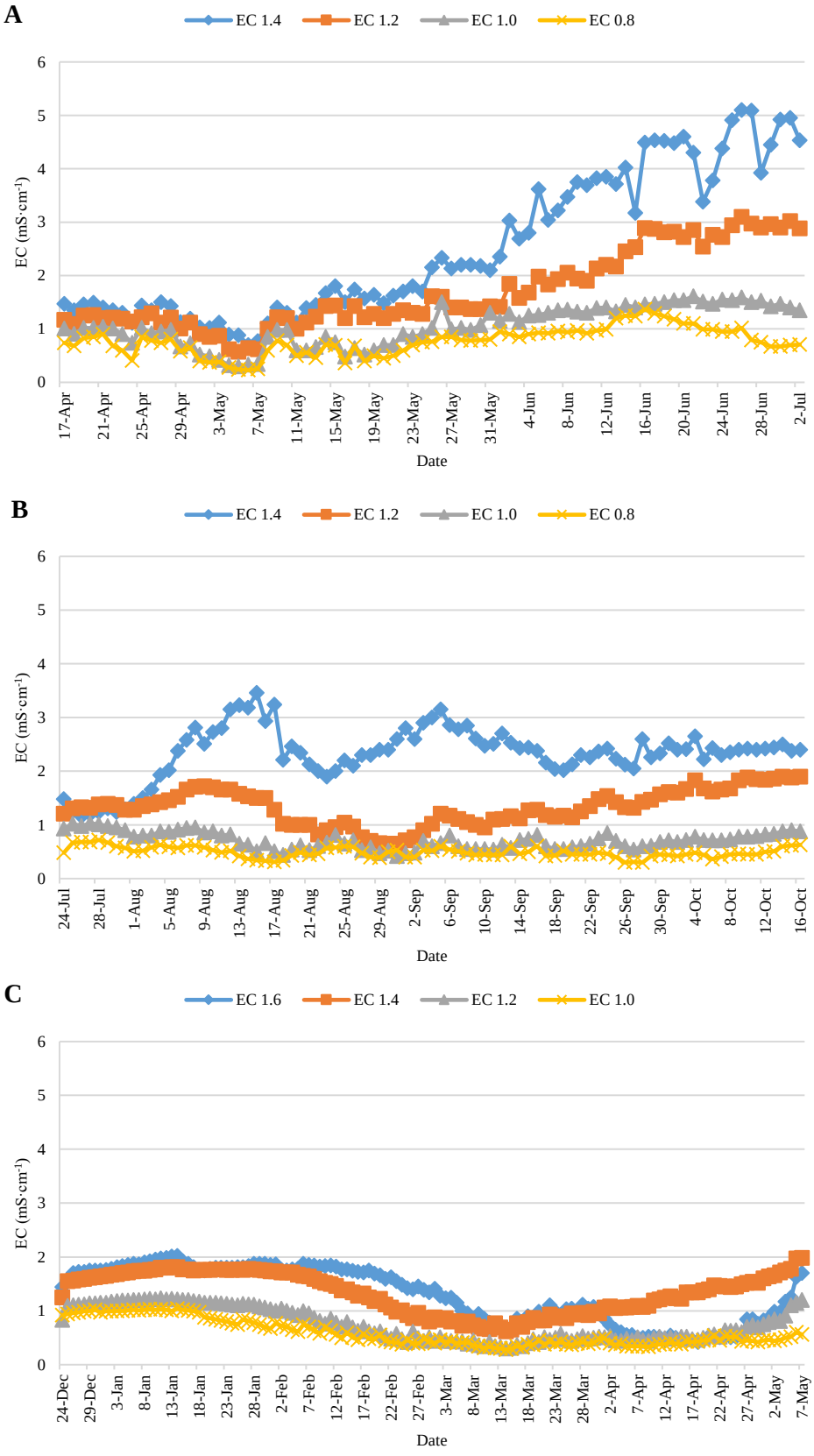


Figure 2. The time course of nutrient solution concentrations expressed as EC in the spring (A), summer (B), and winter (C) production cycles

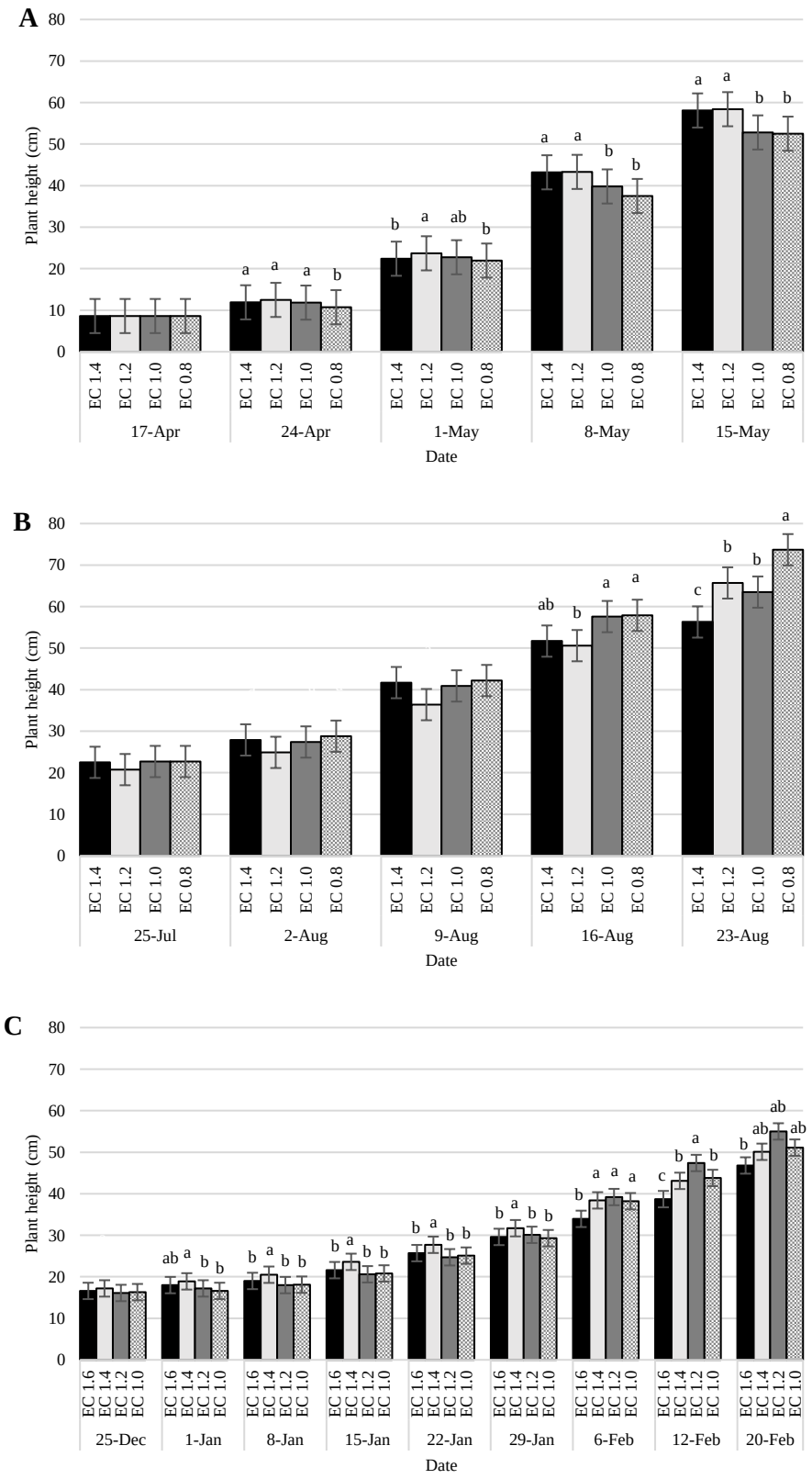


Figure 3. Effect of nutrient solution concentration expressed as EC on plant height during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 10, p = 0.05. Vertical bars on each data point represent the standard error

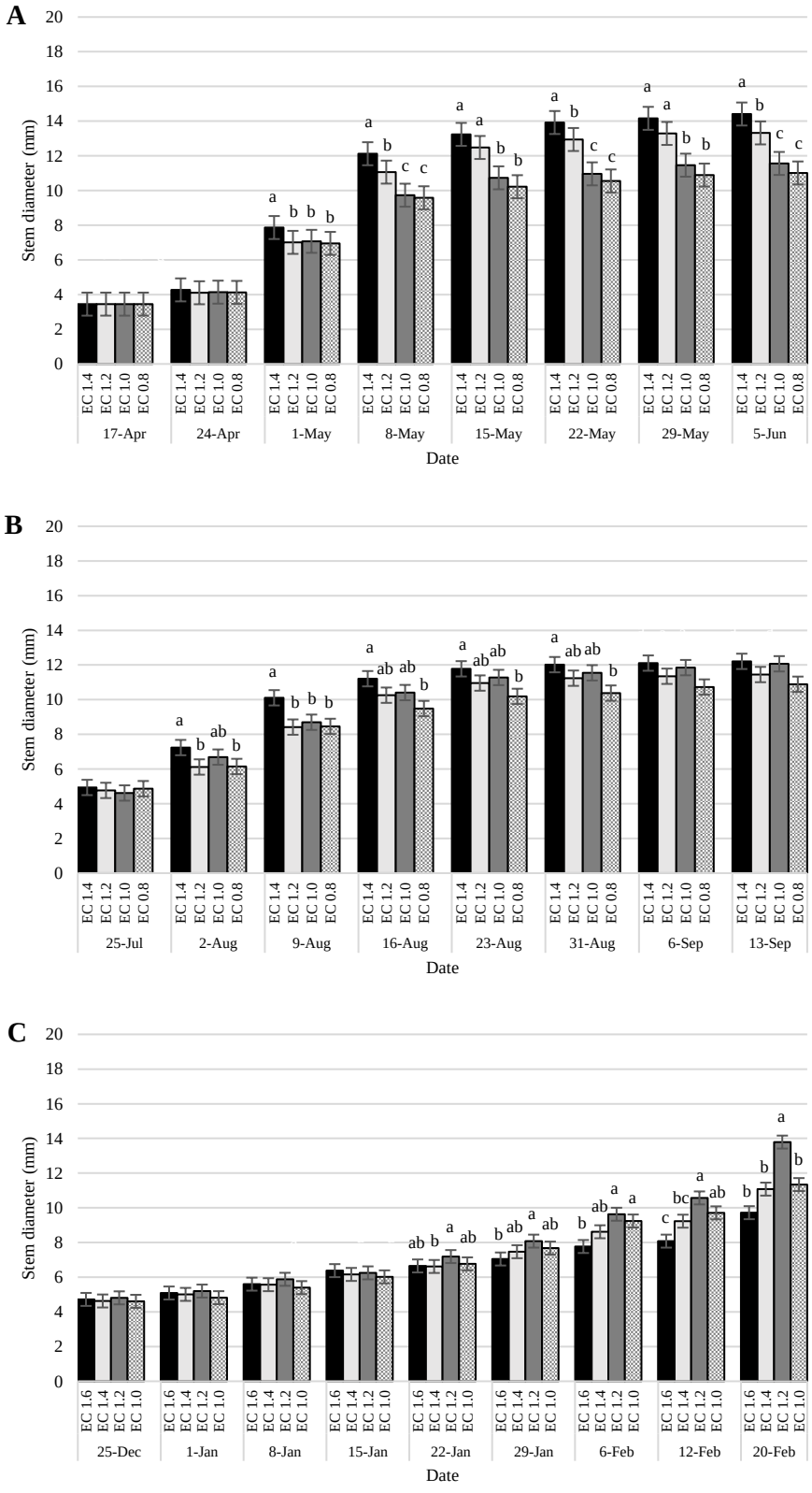


Figure 4. Effect of nutrient solution concentration expressed as EC on stem diameter during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 10, p = 0.05. Vertical bars on each data point represent the standard error

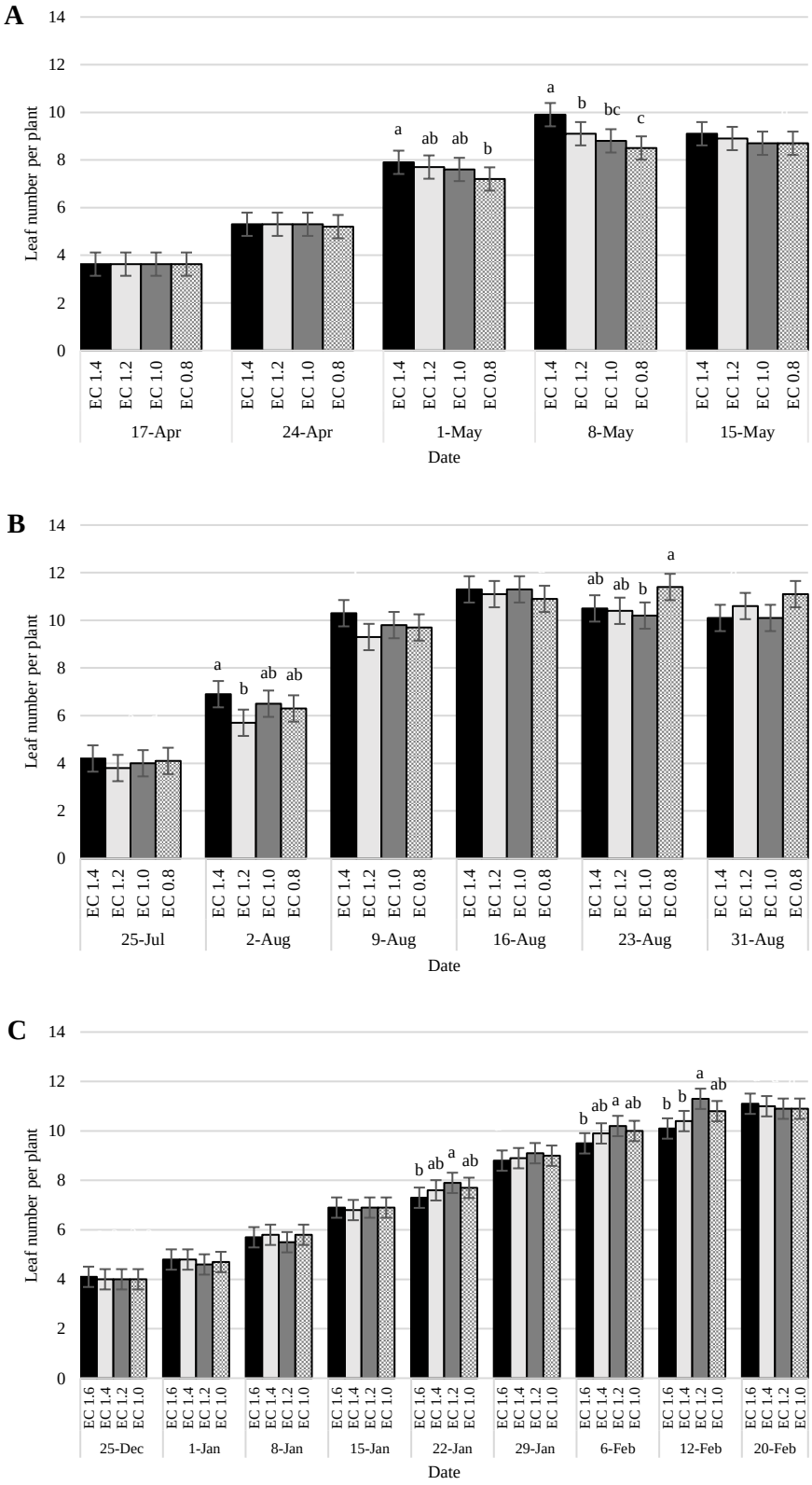


Figure 5. Effect of nutrient solution concentration expressed as EC on the leaf number per plant during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 10, p = 0.05. Vertical bars on each represent the standard error

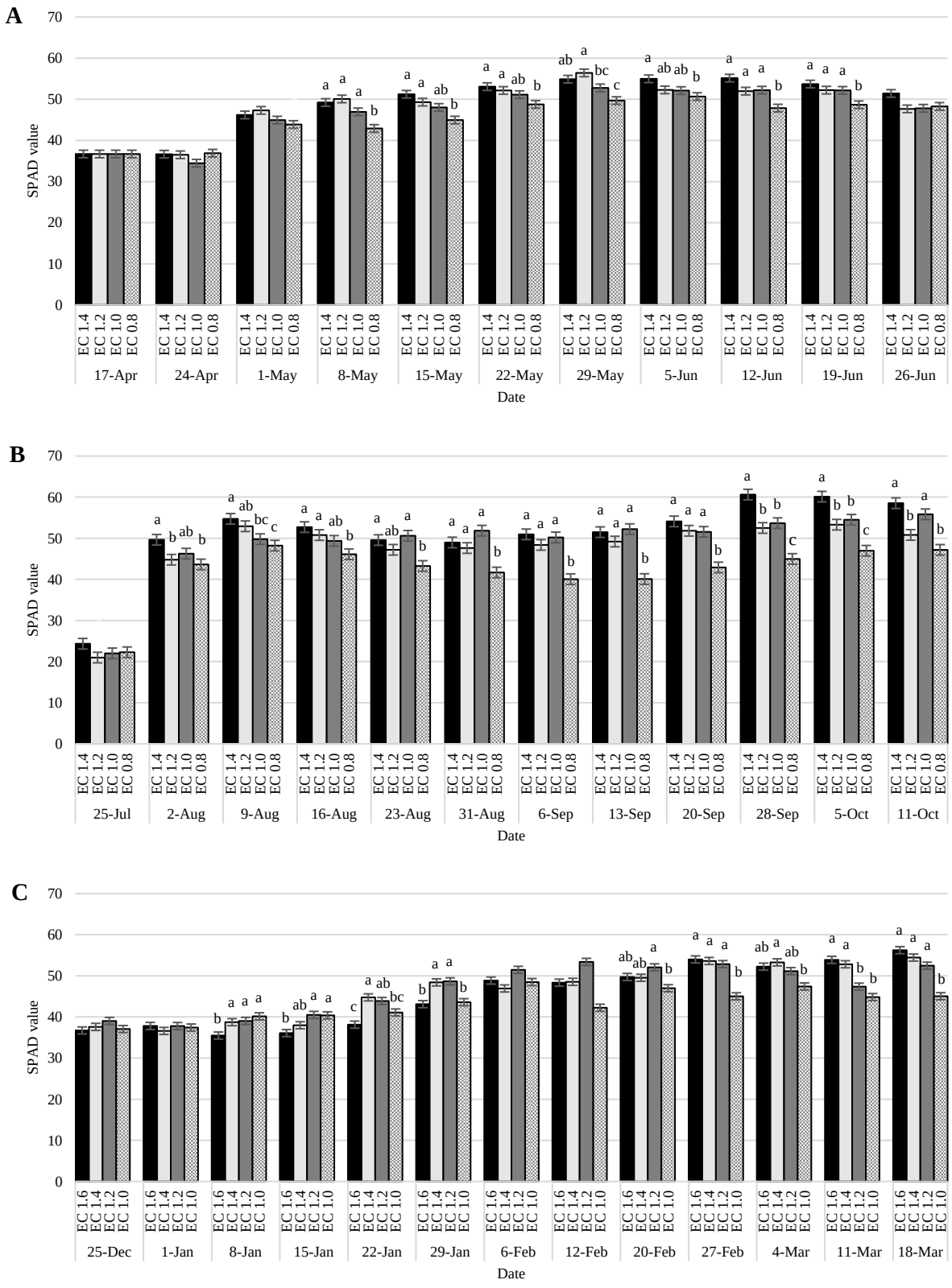


Figure 6. Effect of nutrient solution concentration expressed as EC on intensity of leaf color during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 10, p = 0.05. Vertical bars on each data point represent the standard error

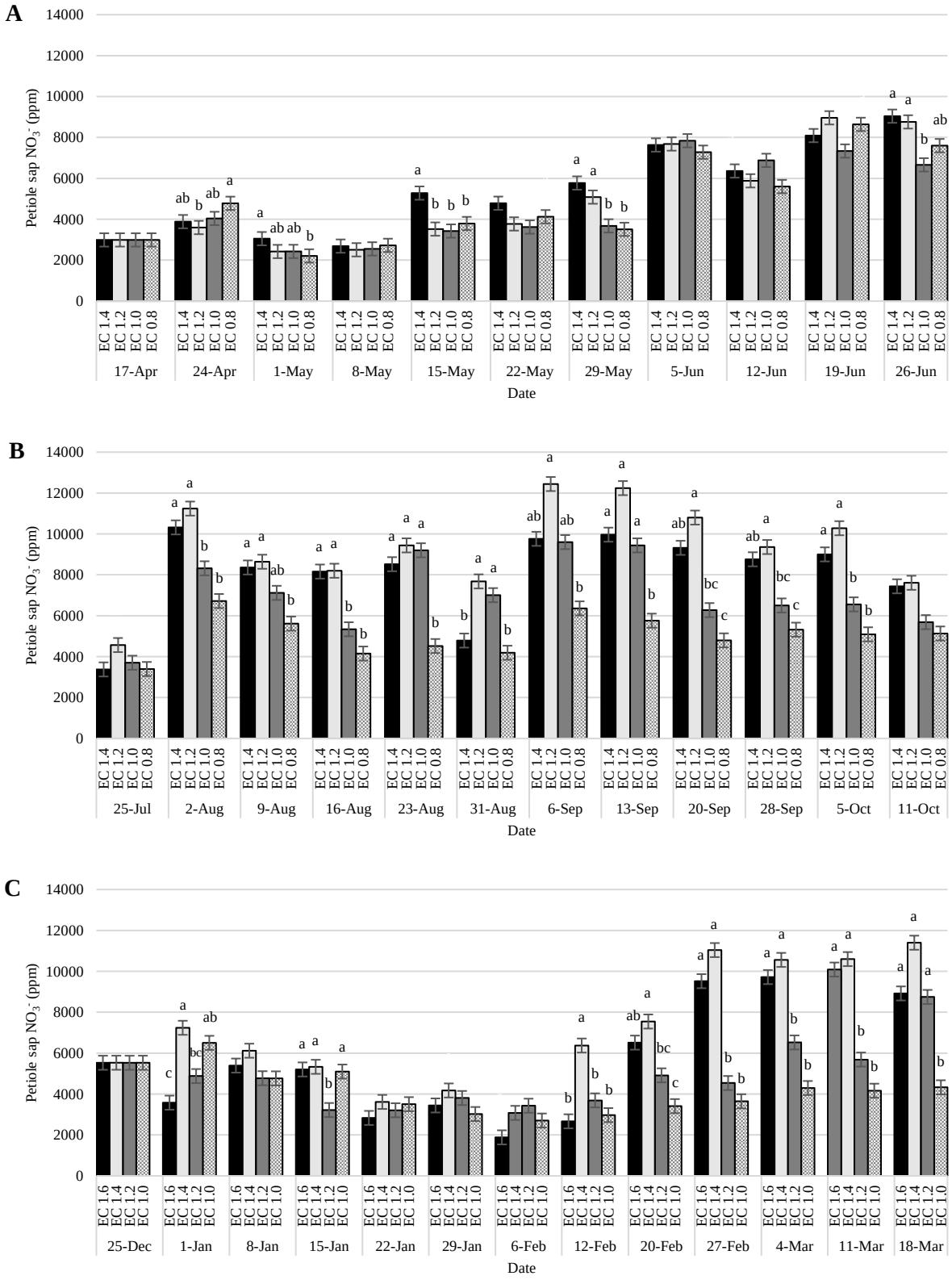


Figure 7. Effect of nutrient solution concentration expressed as EC on nitrate concentration in petiole sap during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 10, p = 0.05. Vertical bars on each data point represent the standard error

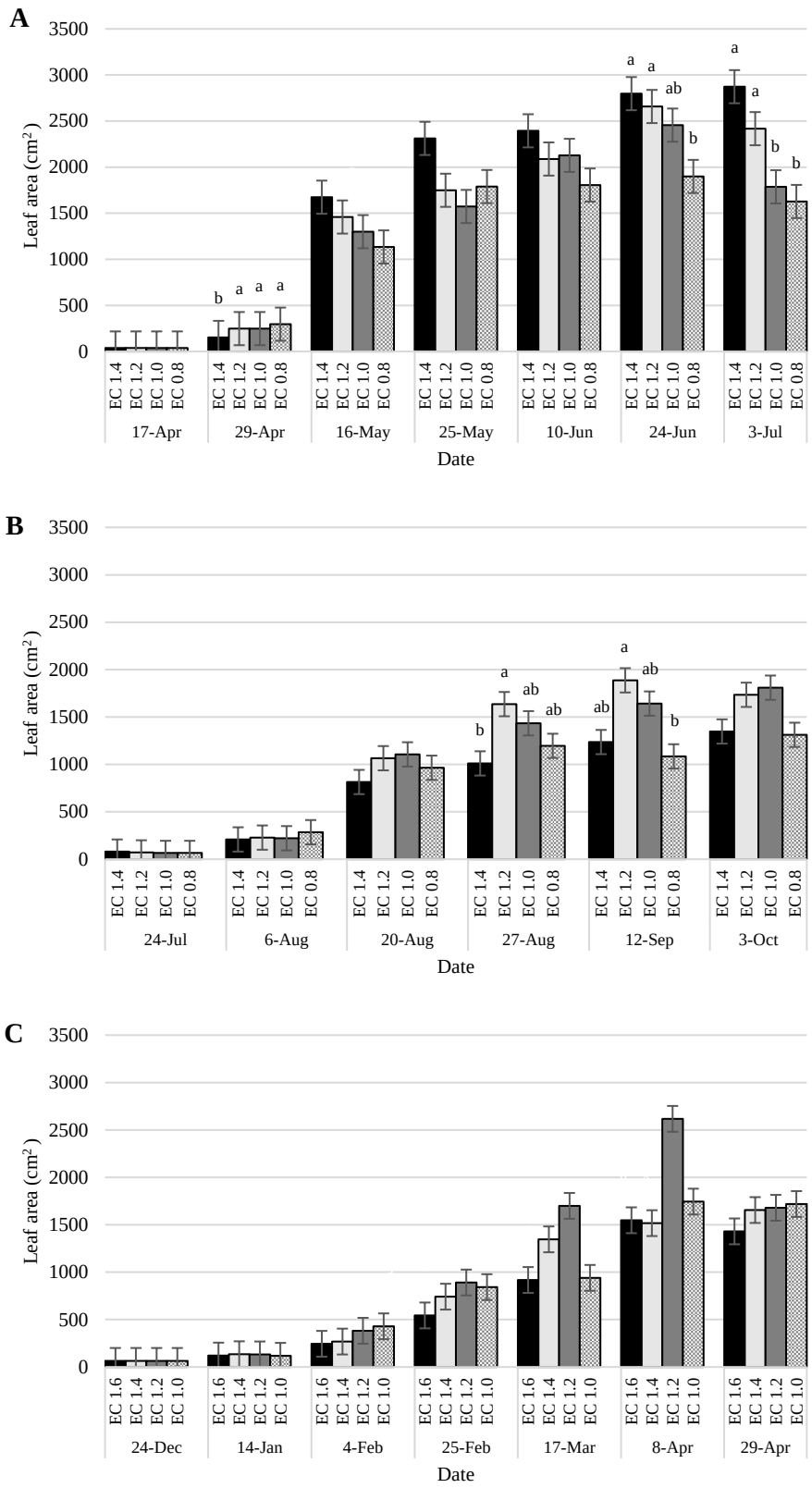


Figure 8. Effect of nutrient solution concentration expressed as EC on leaf area during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 4, p = 0.05. Vertical bars on each data point represent the standard error

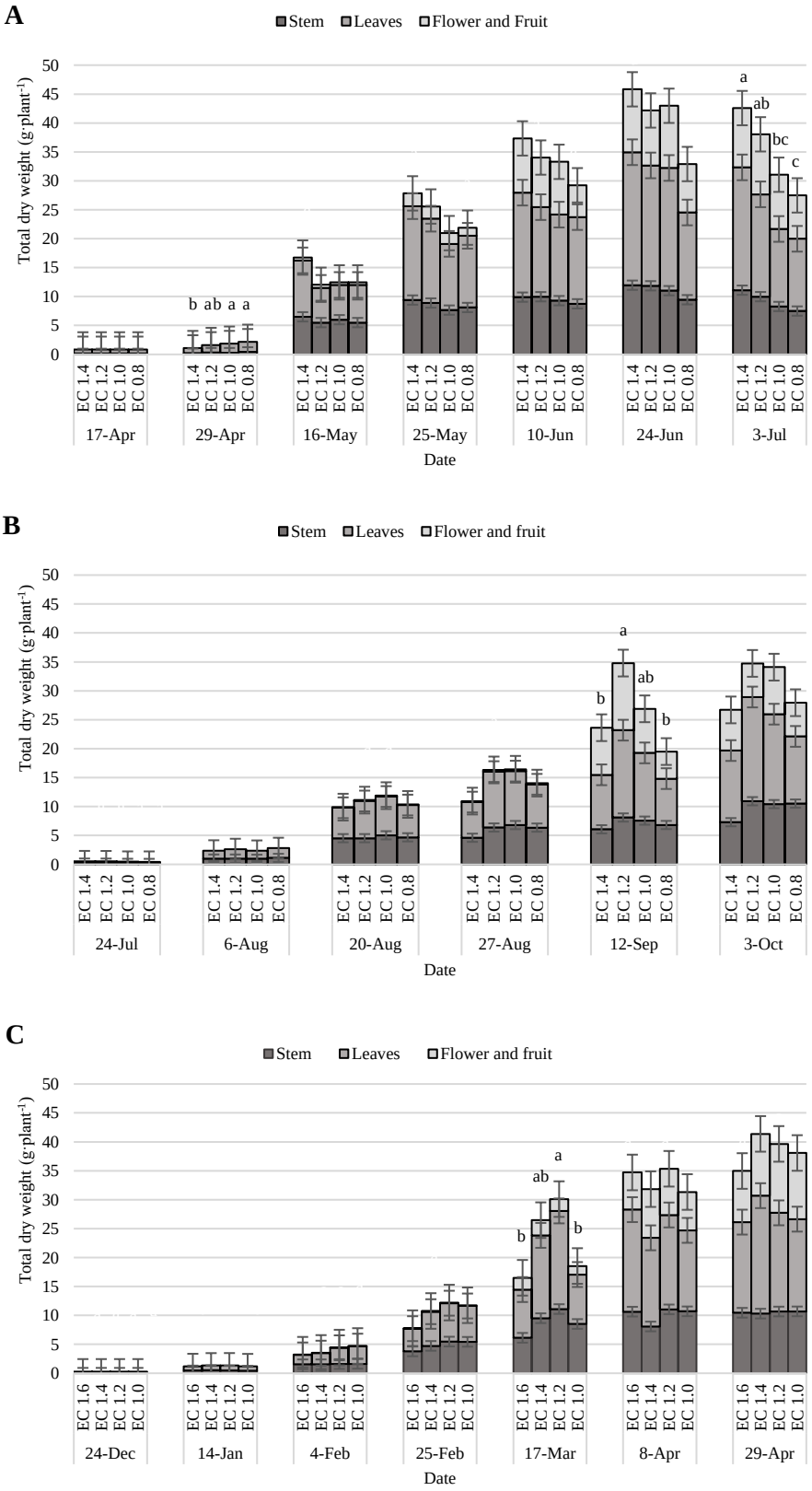


Figure 9. Effect of nutrient solution concentration expressed as EC on the dry weight of whole plant (stem + leaves + flowers and fruit) during the spring (A), summer (B), and winter (C) production cycles

The same letters indicate nonsignificant differences as determined by multiple comparisons using the Tukey's HSD test. n = 4, p = 0.05. Vertical bars on each data point represent the standard error

The marketable yield and fruit quality

In the spring cycle, the marketable fruit yields at the 1.4 and 1.2 EC were higher than at the 1.0 and 0.8 EC (Table 1). Simultaneously, mean fruit weights at the 1.2 and 1.4 EC were higher than those of the 0.8 EC (Table 1). Only a small number of cracked fruits were found in our study, but no differences between the tested treatments were observed (Table 1). The incidence of fruits affected by BER was negligible (data not shown).

During the summer, the number and yields of marketable fruit at the 1.2 and 1.0 EC were greater than those of the 1.4 and 0.8 EC (Table 1). Cracked fruits were observed in all treatments; however, the number of cracked fruits per plant at the 1.0 EC was higher than at the 1.4 EC (Table 1).

In the winter cycle, the highest marketable yield was found at 1.4 EC and the lowest at the 1.6 EC (Table 1). Simultaneously, plants at 1.2 EC produced a higher marketable yield than those of the 1.0 EC (Table 1). Fruit from the 1.4 and 1.2 EC were bigger than those from the 1.6 EC (Table 1). There was no difference in the incidence of cracked fruits between the treatments (Table 1).

In the spring cycle, fruit at the 1.4 EC had higher SSC than the other treatments (Table 2). However, the fruit acidity in this treatment was similar to the other treatments. The SSC to acidity ratio values did not differ between the tested treatments (Table 2). Similarly, as in the spring cycle, in the summer, fruit at the 1.4 EC had the highest SSC (Table 2). Additionally, those fruits also contained more organic acids than in the other treatments (Table 2). However, fruit at the 1.2 EC had a higher SSC to acidity ratio than fruit at the 1.4 EC (Table 2). In winter, SSC, acidity, and the ratio of SSC to acidity in fruit did not differ between the tested treatments (Table 2).

Nutrient uptake

In the spring cycle, the daily uptake rates of N, P, K, Mg, and Ca by plants grown at the 1.4 EC were greater than at the 1.0 and 0.8 EC (Table 3). During the summer, the lowest amounts of absorbed P, K, Mg, and Ca were found at the 0.8 EC (Table 3). However, the N uptake was higher at the 1.4 and 1.2 treatments compared to 0.8. In the winter cycle, uptake rates of all nutrients did not differ between the tested treatments (Table 3).

Table 1. Effect of nutrient solution concentration expressed as EC on yield of marketable tomato fruit and their appearance in the spring, summer, and winter production cycles

Production cycle	Treatment	Fine fruit (number per plant)	Fine fruit (g per plant)	Mean fruit weight (g)	Cracked fruit (number per plant)
Spring	EC 1.4	3.8 ± 0.06	723.8 ± 4.0 a	186 ± 3.7 a	0.07 ± 0.01
	EC 1.2	3.7 ± 0.07	706.7 ± 11.2 a	191 ± 4.7 a	0.04 ± 0.01
	EC 1.0	3.7 ± 0.07	625.8 ± 20.8 b	172 ± 6.51ab	0.08 ± 0.02
	EC 0.8	3.8 ± 0.08	573.1 ± 20.5 b	150 ± 7.3 b	0.06 ± 0.01
Summer	EC 1.4	0.5 ± 0.11 b	62.8 ± 18 b	118.4 ± 9.9	0.06 ± 0.01 b
	EC 1.2	1.2 ± 0.11 a	173.7 ± 22 a	141.1 ± 7.5	0.13 ± 0.03 ab
	EC 1.0	1.1 ± 0.15 a	155.0 ± 15.8 a	132.9 ± 8.2	0.19 ± 0.04 a
	EC 0.8	0.6 ± 0.09 b	68.3 ± 8.2 b	115.8 ± 8.9	0.1 ± 0.01 ab
Winter	EC 1.6	2.1 ± 0.04	220.6 ± 0.21d	104.4 ± 2.1b	0.7 ± 0.09
	EC 1.4	2.2 ± 0.08	270.1 ± 0.41a	119.7 ± 4.9a	0.6 ± 0.09
	EC 1.2	2.2 ± 0.04	267.0 ± 0.40b	121.3 ± 2.3a	0.9 ± 0.09
	EC 1.0	2.3 ± 0.04	259.0 ± 0.40c	113.1 ± 1.9ab	0.7 ± 0.09

Same letters in a column within each production cycle indicate nonsignificant differences based on the multiple comparisons of the Tukey's HSD test ($p < 0.05$)

Table 2. Effect of nutrient solution concentrations expressed as EC on soluble solid concentration and acidity of tomato fruit in the spring, summer, and winter production cycles

Production cycle	Treatment	SSC (%)	Acidity (%)	SSC to acidity ratio
Spring	EC 1.4	5.4 ± 0.12 a	0.75 ± 0.02	7.4 ± 0.4
	EC 1.2	4.8 ± 0.15b	0.75 ± 0.02	6.5 ± 0.3
	EC 1.0	4.7 ± 0.13b	0.69 ± 0.01	6.8 ± 0.3
	EC 0.8	4.7 ± 0.18b	0.66 ± 0.03	7.4 ± 0.4
Summer	EC 1.4	5.4 ± 0.08 a	0.95 ± 0.04 a	5.8 ± 0.3 b
	EC 1.2	4.9 ± 0.15 b	0.69 ± 0.02 b	7.2 ± 0.2 a
	EC 1.0	4.8 ± 0.13 b	0.73 ± 0.03 b	6.7 ± 0.2 ab
	EC 0.8	4.7 ± 0.11 b	0.71 ± 0.03 b	6.8 ± 0.3 ab
Winter	EC 1.6	6.1 ± 0.13	0.78 ± 0.04	9.3 ± 1.9
	EC 1.4	5.7 ± 0.15	0.71 ± 0.03	8.1 ± 0.2
	EC 1.2	5.9 ± 0.17	0.74 ± 0.04	8.1 ± 0.3
	EC 1.0	6.1 ± 0.06	0.71 ± 0.03	8.9 ± 0.5

Same letters in a column within each production cycle indicate nonsignificant differences based on the multiple comparisons of the Tukey's HSD test ($p < 0.05$)

Table 3. Daily uptake of macronutrients by tomato plants during the spring, summer, and winter production cycles

Treatment	N (mg per plant)	P_2O_5 (mg per plant)	K_2O (mg per plant)	MgO (mg per plant)	CaO (mg per plant)
EC 1.4	26.22 ± 3.30a	12.90 ± 1.69a	56.05 ± 7.34a	10.12 ± 1.32a	27.64 ± 3.62a
EC 1.2	18.10 ± 2.43ab	8.74 ± 1.20ab	37.96 ± 5.21ab	6.85 ± 0.94ab	18.72 ± 2.57ab
EC 1.0	13.84 ± 1.68b	6.73 ± 0.78b	29.24 ± 3.39b	5.27 ± 0.61b	14.41 ± 1.67b
EC 0.8	9.39 ± 1.14b	4.50 ± 0.54b	19.58 ± 2.34b	3.53 ± 0.42b	9.65 ± 1.15b
EC 1.4	14.51 ± 2.17a	6.77 ± 0.89a	29.44 ± 3.87a	5.31 ± 0.70a	14.52 ± 1.91a
EC 1.2	19.06 ± 1.62a	9.08 ± 0.74a	39.47 ± 3.24a	7.12 ± 0.58a	19.46 ± 1.59a
EC 1.0	13.92 ± 0.94ab	6.74 ± 0.54a	29.28 ± 2.38a	5.28 ± 0.43a	14.44 ± 1.17a
EC 0.8	8.46 ± 0.57b	4.09 ± 0.29b	17.79 ± 1.27b	3.21 ± 0.23b	8.77 ± 0.62b
EC 1.6	10.10 ± 3.17	3.52 ± 0.87	14.05 ± 3.49	2.98 ± 0.74	8.14 ± 2.02
EC 1.4	15.00 ± 3.26	5.63 ± 1.16	22.47 ± 4.63	4.76 ± 0.98	13.02 ± 2.68
EC 1.2	13.80 ± 3.42	5.31 ± 1.22	21.18 ± 4.86	4.49 ± 1.03	12.27 ± 2.81
EC 1.0	10.01 ± 2.48	3.96 ± 0.97	15.80 ± 3.89	3.35 ± 0.82	9.15 ± 2.25

Same letters in a column within each production cycle indicate nonsignificant differences based on the multiple comparisons of the Tukey's HSD test ($p < 0.05$)

DISCUSSION

Tomato species are believed to be sensitive to specific abiotic stresses, such as high temperatures and radiation, drought, and salinity (Vazquez-Cruz et al. 2012). Simultaneously, it has been proven that the vegetative and reproductive responses of tomatoes are strongly affected by their nutritional status, which is determined by the availability of macro- and micronutrients in the root environment and also moisture and salinity of the medium (Adams et al. 1973; Okano et al. 2000).

In our study, plants grown in the summer cycle were taller than those in the spring and winter (Fig. 3) due to more favorable growth conditions. It was particularly pronounced when

tomatoes were supplied with the nutrient solution at the lowest EC value. We also found that irrespective of the production cycle, the final number of leaves per plant remained consistent among the tested treatments (Fig. 5). However, during the summer and winter cycles, the plants had more leaves than those in the spring cycle, which can be attributed to the delayed development of the first flower cluster (Okano et al. 2001). The development of flowers is essential for the subsequent production of fruits, and any postponement in the flowering process can result in corresponding delays in fruit formation (Atherton & Harris 1986). It should be noted that an increased leaf area was recorded only at the 1.2 and 1.4 treatments during the spring and at the 1.0 and 1.2 EC in the summer cycle (Fig. 8). The above information indicates that the optimal range of EC values of nutrient solutions used in a single-truss production system of tomatoes depended on the period of their cultivation. A similar result was obtained in long-period cultivation (Masuda et al. 1989).

During the spring production cycle, a direct relationship was observed between enhanced plant growth (height, stem diameter, and leaf area) and the higher uptake rates of critical nutrients such as N, P, K, Mg, and Ca. It suggests favorable growth conditions, particularly at the 1.4 and 1.2 EC, contributed to elevated nutrient uptake. In line with these observations, Adams et al. (1973) showed that increasing nitrogen concentration led to taller plants, longer leaves, more flowers and marketable fruits, a higher mean fruit weight, and an overall increase in the total yield of the plants. Notably, lower levels of nitrogen were associated with delayed harvesting. The lower SPAD values observed in plants subjected to lower nutrient concentrations during all cycles can be related to the reduced nitrate content in the petiole sap. These findings collectively indicate that nutrient availability and uptake are crucial in enhancing plant growth and chlorophyll content.

One of the critical factors influencing plant yield is the timing and intensity of flowering (Hurd & Cooper 1967). In our study, the first flower cluster developed earlier in the spring compared to the summer and winter cycles. Simultaneously, fruit yields in the spring cycle were higher than in the other production cycles (Table 1). We believe that in the summer cycle, the scorching air temperatures during planting and a rapid drop in air temperature during the flowering stage could reduce the fruit number and yield. According to Sato et al. (2004) and Wada et al. (2006), minimizing the adverse effects of high temperatures and their variations during the summer on the reproductive response of tomatoes' growth under greenhouse conditions can be achieved by the cultivation of a heat-tolerant cultivar or by implementing shading during critical growth stages. Regardless, in the spring cycle, a single plant across all treatments produced nearly four high-quality fruits with the highest yields and largest fruits at the 1.2 and 1.4 treatments (Table 1). In the summer and winter cycles, the highest marketable yields were found at the 1.0 and 1.2 treatments and the 1.4 treatment, respectively. In the summer cycle, the increased fruit yields at the 1.0 and 1.2 treatments were related to a greater number of high-quality fruits per plant. In the case of the winter cycle, the enhanced fruit yield at the 1.4 treatment was associated with a higher fruit size.

Consumers prefer high-quality tomato fruit, which can be produced even under salinity stress conditions, as Mitchell et al. (1991) demonstrated. In saline conditions, tomato fruits often exhibit reduced size due to the limited uptake of water and its transport to the fruit tissues (Bolarin et al. 2001). In our study, the highest salinity of nutrient solution reduced fruit size only in the winter cycle (Table 1). Thus, regardless of the production season, an EC level of 1.4 $mS \cdot cm^{-1}$ of the nutrient solution is safe for tomatoes.

Interestingly, salinity stress is positively associated with BER incidence and negatively correlated with fruit cracking (Saito et al. 2006). Araki et al. (2009) reported producing smaller tomato fruit with increased SSC by applying short-term salt stress. Dorais et al. (2001) demonstrated that tomato fruit quality, including SSC, can be improved at salinity levels of 3.5 to 9.0 $mS \cdot cm^{-1}$. Our study found

an increased SSC in fruit at the highest EC value of the nutrient solution used, but only in the spring and summer cycles (Table 2). Notably, this effect in the spring cycle was recorded without reducing fruit yield (Table 1).

CONCLUSIONS

The results obtained in this study indicated that vegetative and reproductive responses, as well as the fruit quality of tomatoes cultivated in a single-truss system in a hydroponic culture, were affected by the EC values of the nutrition solutions used. The optimal plant parameters, including yields and fruit quality, were found when EC values of the nutrient solutions were 1.2–1.4 $mS \cdot cm^{-1}$ for the spring, summer, and winter production cycles.

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