Research Article

Received: 4 February 2013 Revised: 4 April 2013 Accepted article published: 23 April 2013 Published online in Wiley Online Library:

(wileyonlinelibrary.com) DOI 10.1002/jsfa.6191

Effects of climatic control on tomato yield and nutritional quality in Mediterranean screenhouse

Rocío Leyva,[a,b]* Christian Constán-Aguilar,[b] Begoña Blasco,[b] Eva Sánchez-Rodríguez,[b] Luis Romero,[b] Teresa Soriano[a] and Juan M Ruíz[b]

Abstract

BACKGROUND: The quality of vegetables for fresh consumption is a complex issue. In this study the yield and quality of cherry tomato fruits were assessed under different environmental control conditions, namely in a screenhouse (S), in a screenhouse equipped with a fogging system (SF) and in a screenhouse with complements such as plastic sheeting to maintain the microclimate created by the fogging system (SFS), as well as under open field (OF) cultivation. Levels of vitamin C, carotenoids (lycopene, β-carotene and lutein), phenolic compounds (flavonoids and phenolic acids), sugars (fructose, glucose and sucrose), organic acids (citric acid and malic acid) and flavour indices were measured. The aim of the study was to determine how different environmental control technologies could influence production and quality traits in tomato cherry fruits cultivated in a Mediterranean area.

RESULTS: The results showed that the fogging system treatment's decline in maximum vapour pressure deficit (by 0.7 kPa compared with OF cultivation), increase in mean fruit weight (by about 4 g per fruit) and low radiation and temperature values may exert a positive effect on lycopene accumulation.

CONCLUSION: For the production and nutritional parameters measured, it is postulated that the fogging system treatment offers a better balance between production and nutritional quality. This treatment proved to be best in terms of productivity, vitamin C and lycopene contents and antioxidant capacity.

Keywords: *Solanum lycopersicum*; lycopene; fogging system; screenhouse; flavonoids; carotenoids

INTRODUCTION

Tomato, a major component of the traditional Mediterranean diet, has been found to be associated with a low rate of mortality due to cardiovascular diseases.[1] Its major active compounds are vitamin C, carotenoids (lycopene, β-carotene and lutein), flavonoids and phenolic acids.[2] Recently, consumer demand has increased greatly for these traits as well for minerals, vitamins and bioactive substances.[3] Vitamin C (ascorbic acid), while being a most effective antioxidant in plants, is also an important photochemical of tomato fruit. Apart from vitamin C, lycopene has the highest antioxidant activity among all dietary antioxidants[4] and is the main factor on which the colour of red tomatoes depends.[5] Tomatoes also contain moderate amounts of α-carotene, β-carotene and lutein.[6] A precursor of vitamin A, β-carotene is abundant in tomato but is of lower nutritional importance than lycopene, as it constitutes only 7% (w/w) of the total content of the fruit.[7] Although more studies are needed, the antioxidant role of these carotenoids in animals has been reported to exert a modest hypocholesterolaemic effect,[8] suggesting that tomato consumption may reduce the risk of cardiovascular diseases via decreased cholesterol synthesis.[9] Other potential action mechanisms by which tomato carotenoids may prevent cancer are by inducing apoptosis and inhibiting growth.[10]

The levels of these beneficial compounds in tomatoes are known to vary depending on the cultivar, ripening stage and growth conditions as well as the level of exposure to environmental stress.[11] High light intensity can lead to disorders in the development and appearance of tomato fruits.[12] Murneek *et al*.[13] suggested that relatively high temperatures probably cause a decrease in ascorbic acid content via oxidation. Meanwhile, Liptay *et al*.[14] postulated that vitamin C accumulation in tomato fruits seems also to be directly correlated with temperature. Therefore, normally, open field cultivation leads to a higher ascorbic acid content than greenhouse cultivation, as does harvesting in late summer compared with other seasons.[15] Lycopene formation and accumulation have been shown by Davey *et al*.[16] to be

* *Corresponding Author: Rocío Leyva, IFAPA, Institute of Research and Training in Agriculture and Fisheries, Granada, Spain and Department of Plant Physiology, Faculty of Sciences, University of Granada, Granada, Spain. E-mail: roleyva@ugr.es*

a *IFAPA, Institute of Research and Training in Agriculture and Fisheries, Granada, Spain*

b *Department of Plant Physiology, Faculty of Sciences, University of Granada, Granada, Spain*

conditioned by higher temperatures (>32 °C), while Dumas *et al*.[1] postulated that, under high solar radiation, lycopene is inhibited mainly by conversion into β-carotene. For a tomato crop cultivated in a Mediterranean area, Rosales *et al*.[17] demonstrated that the lycopene content declined when temperatures, solar radiation and vapour pressure deficit (VPD) were highest. These conditions also encourage an increase in other antioxidant parameters such as total phenols, flavonoids and ascorbic acid, indicating a stronger antioxidant capacity in cherry tomato fruits.[17] Moreover, phenolic biosynthesis is particularly sensitive to various types of abiotic stress.[18] In fact, the flavonoid content may be enhanced in response to intense light, in particular to increased UV-B radiation.[19]

The organoleptic characteristics of tomato fruits depend mainly on their levels of soluble sugars (glucose, fructose and sucrose) and organic acids (citric acid and malic acid), which are important to tomato taste.[20] For a tomato crop cultivated in summer, Wada *et al*.[21] reported that fruit quality was characterised by a lower sugar content and that titratable acidity increased with high air temperatures.

The climate in Mediterranean regions is characterised by long, hot summers, high solar radiation flux, dusty and dry weather and limited water resources.[22] These stressful conditions require environmental control devices to improve the production and quality of tomato fruits. Netting is frequently used to protect agricultural crops from excessive solar radiation, thus improving the thermal regime,[23] and is applied over net-house constructions (screenhouses). Romero-Gámez *et al*.[24] proposed the expansion of the use of these structures in inland areas when environmental conditions are stressful, such as during the summer season in the Mediterranean basin. Actually, screenhouses are combined with greenhouse technologies[25] focused on optimising environmental conditions to maximise plant growth and development rate as well as product quality. Excessively high temperatures and low ambient humidity can be offset by using a fogging system as a cooling method to improve the microclimate inside screenhouses. In this context, the aim of the present study was to determine how environmental control technologies such as a fogging system with plastic sheeting could influence the production and quality parameters of tomato cherry fruits cultivated in a screenhouse during summer in a Mediterranean area.

EXPERIMENTAL

Plants and growth conditions

Cherry tomato (*Solanum lycopersicum* L. cv. Alina) seedlings were grown for 30 days in a tray with wells (each 3 cm × 3 cm × 10 cm) in the nursery Semillero Saliplant SL (Carchuna, Granada). Grafting on Maxifort rootstock was performed when the seedlings had developed three or four true leaves. Two weeks after grafting, tomato plants were transferred to a screenhouse located in the IFAPA Centre Camino de Purchil (Granada, Spain; latitude 37° 10′ 21″ N, longitude 3° 38′ 10″ W). The experiment was conducted from June to November 2010. The plants were cultivated at a density of 2.2 plants m^{-2}. Water and fertiliser were delivered by an automated drip irrigation system using a complete nutrient solution with an electrical conductivity of 1.9 dS m^{-1}. The pH of the nutrient solution was measured daily and, when necessary, corrected with 1 mol L^{-1} orthophosphoric acid to maintain the pH at 6.2–7. The growth period was 152 days during the summer period. All lateral shoots were removed periodically. This design was conducted for two cycles in the summer season (2010 and 2011). Similar trends were observed in the samplings measured each year.

Measurements of environmental parameters

Over the entire fruit production cycle, air temperature (T^a) and environmental relative humidity (RH) were measured using four HMP45 probes (Vaisala, Helsinki, Finland), while incident solar radiation was measured using four SKS1110 pyranometer sensors (Skye Instruments, Llandrindod Wells, UK). A CR-10 data logger (Campbell Scientific Inc., Logan, UT, USA) stored the average values for three measurements every 30 min. Data were expressed as daily maximum T^a, RH and VPD during the 12:00–18:00 local time.

Experimental design and fogging treatments

The experimental design was a randomised complete block design with four treatments. A greenhouse structure was covered with a black-and-white polyethylene mono-filament screen of 9 × 6 strands cm^{-2} to produce an enclosure called a screenhouse. Measurements were made in three distinct screenhouse compartments involving (1) no environmental control (S), (2) active environmental control limited to a low-pressure fogging system (SF) and (3) plastic sheeting coupled with a fogging system to prevent evaporative losses through the screen (SFS). Finally, a cherry tomato crop was cultivated in an open field (OF). The treatments began 22 days after transplanting (DAT) and were maintained for as long as conditions allowed.

The cooling effect of the fogging system in the SF and SFS treatments was activated when the VPD was higher than 2.5 kPa between 12:00 and 18:00 inside the greenhouse. The density of low-pressure nozzles (7 L h^{-1}) was 0.13 nozzles m^{-2}. The complementary plastic sheeting had a high content of ethylene vinyl acetate and an average thickness of 200 µm. The plastic sheeting was activated simultaneously with the fogging system.

Fruit harvest

In each sampling, the total, commercial and non-commercial yields of tomato fruits as well as mean fruit weight and fruit dry weight were measured. Uniformly ripe healthy fruits at the red-ripe stage were harvested at 87 DAT. The tomatoes were rinsed three times in distilled water after disinfection with 10 mL L^{-1} Triton X-100. For each treatment, 15–20 fruits from different plants were harvested. Later, fruits were homogenised and immediately frozen in liquid nitrogen and stored at −30 °C for subsequent biochemical determinations. Samples of fresh tissues from the tomato fruits were used to analyse the parameters described below.

Vitamin C content by high-performance liquid chromatography with UV–visible diode array detection (HPLC-UV-DAD)

The assay was performed using HPLC-UV-DAD (Agilent Technologies, Waldbronn, Germany) under the following conditions: Phenomenex Luna reverse phase column, 250 mm × 4.6 mm i.d., 5 µm, Li-Chrospher 100 RP-18, with a 4 mm × 4 mm i.d. guard column of the same material (Phenomenex, Utrecht, Belgium); column oven temperature, 28 °C. The determination of vitamin C (ascorbic acid) was based on the method of Hejtmánková *et al*.[26] with slight modifications. About 0.2 g of frozen fresh tomato sample was homogenised with 1 mL of 30 mL L^{-1} metaphosphoric acid. The resulting mixture was centrifuged for 10 min,

filtered through a 0.45 μm membrane filter and analysed by HPLC-UV-DAD. A single mobile phase consisting of 2.5 mmol L^{-1} sulfuric acid at 1 mL min^{-1} was used. The elution was monitored at 250 nm. L-Ascorbic acid was used as a standard, eluting at 4.1 min.

Carotenoids: lycopene, β-carotene and lutein

Carotenoid extraction was performed directly in a 2 mL Eppendorf tube containing an assay sample of about 400 mg of tomato powder. It was achieved by means of alternating periods of agitation and centrifugation (19 500 × *g*) in the following order: addition of 100 μL of saturated aqueous sodium chloride solution and 50 μL of hexane, agitation for 30 s and centrifugation for 2 min; addition of 200 μL of dichloromethane, agitation for 30 s and centrifugation for 2 min; addition of 1000 μL of ethyl acetate, agitation for 30 s and centrifugation for 5 min. An aliquot of the organic fraction (upper phase) was filtered and assayed by HPLC.[27]

The assay was performed using HPLC-UV-DAD (Agilent Technologies) under the following conditions: Phenomenex Luna reverse phase column, 250 mm × 4.6 mm i.d., 5 μm, Li-Chrospher 100 RP-18, with a 4 mm × 4 mm i.d. guard column of the same material (Phenomenex); column oven temperature, 28 °C; mobile phase, acetonitrile/ultrapure water/ethyl acetate (53:7:40 v/v/v); flow rate of mobile phase, 1 mL min^{-1}; injection volume, 10 μL; wavelength range, 200–750 nm; three working wavelengths, 474 nm for lycopene, 454 nm for β-carotene and 448 nm for lutein.

Phenolic compounds by HPLC-UV-DAD

The assay was performed using HPLC-UV-DAD (Agilent Technologies) under the following conditions: Phenomenex Luna reverse phase column, 250 mm × 4.6 mm i.d., 5 μm, Li-Chrospher 100 RP-18, with a 4 mm × 4 mm i.d. guard column of the same material (Phenomenex); column oven temperature, 28 °C. For the identification and characterisation of phenolic compounds, the assay was conducted in accordance with the method of Sánchez-Rodríguez *et al*.[28] The mobile phase consisted of two solvents, (A) water/acetic acid (99:1 v/v) and (B) acetonitrile, starting with 5% B and using a gradient to obtain 50% B at 30 min and 80% B at 37 min. The flow rate was 1 mL min^{-1} and the injection volume was 20 μL. Spectral data from all peaks were accumulated in the range 200–400 nm and chromatograms were recorded at 280, 320 and 360 nm.

Antioxidant capacity tests

Total non-enzymatic antioxidant activity was measured using the ferric-reducing ability of plasma (FRAP) and Trolox equivalent antioxidant capacity (TEAC) assays. For both tests, 0.5 g of leaf tissue was homogenised in 5 mL of methanol. The FRAP assay was performed with FRAP reagent, which comprised 1 mmol L^{-1} 2,4,6-tripyridyl-2-triazine and 20 mmol L^{-1} ferric chloride in 0.25 mol L^{-1} sodium acetate (pH 3.6).[29] The TEAC assay was performed following Cai *et al*.[30] 2,2-Azinobis-(3 ethylbenzothiazoline-6-sulfonic acid) (ABTS) radical cation ($ABTS^{\bullet+}$) solution was produced from 7 mmol L^{-1} ABTS and 2.45 mmol L^{-1} potassium persulfate by incubation at room temperature in the dark for 16 h. The $ABTS^{\bullet+}$ solution was diluted with methanol to an absorbance of 0.70 ± 0.02 at 734 nm. Trolox standard solutions (0–656 μmol L^{-1}) in 800 mL L^{-1} methanol were prepared and assayed under the same conditions. Results were expressed as mmol Trolox g^{-1} fresh weight (FW).

The reducing power of tomato fruit was measured following Hsu *et al*.[31] Increased absorbance of the reaction mixture indicated greater reducing power.

A test of the 2,2-diphenyl-1-picrylhydrazyl (DPPH) free radical-scavenging effect was performed according to Hsu *et al*.[31]

Sugar and organic acid contents in tomato fruit extract

Sucrose, D-glucose and D-fructose contents were determined with enzymatic test kits (Roche Biopharm, St Didier au Mont d'Or France) by measuring the formation of NADPH at 340 nm according to the manufacturer's protocol.

The sweetness index was calculated based on the concentration and sweetness of individual carbohydrates.[32] The contribution of each carbohydrate was determined based on the fact that fructose is 2.30 and sucrose 1.35 times sweeter than glucose. Hence the sweetness index was calculated as 1.00 × [glucose] + 2.30 × [fructose] + 1.35 × [sucrose].[33]

Statistical analysis

Data were subjected to analysis of variance, and differences between means were compared by Fisher's least significant difference (LSD) test at a probability level of 95%. Significance levels were expressed as $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$ and NS (not significant), $P > 0.05$.

RESULTS

Effects of environmental conditions on fruit yield

Summer in the Mediterranean basin is characterised by decreased RH, increased solar radiation and higher temperatures. Thus the fogging system showed its best result in enhancing the RH by 39% compared with OF conditions (Table 1). This led to a decline in maximum VPD of 0.7 kPa compared with the OF treatment (Table 1). The radiation integral in the treatments with a cooling system (SF and SFS) showed a reduction in overall radiation of 46–55% compared with the OF treatment during the period of maximum solar radiation (Table 1). However, the SF treatment did not reduce the temperature, which rather increased by 2.2 °C when the fogging system was coupled with plastic sheeting (SFS) (Table 1).

Table 1. Climate data recorded during month preceding harvest of tomato plants under different environmental conditions

Treatment[a]	Average maximum RH (%)	Average maximum VPD (kPa)	Mean solar radiation (MJ m^{-2} day^{-1})	Average maximum air temperature (°C)
S	62.7 ± 2.9	3.5 ± 0.2	16.8 ± 0.7	33.4 ± 0.5
SF	72.1 ± 2.6	3.1 ± 0.1	13.1 ± 0.3	32.4 ± 0.3
SFS	68.5 ± 1.9	3.3 ± 0.1	10.9 ± 0.4	35.6 ± 0.5
OF	52.0 ± 2.0	3.8 ± 0.2	24.4 ± 0.4	33.4 ± 0.5

[a] S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field.

Table 2. Production and weight data of tomato fruits under different environmental conditions

Treatment[a]	Total production (kg per plant)	Commercial production (kg per plant)	Average fruit weight (g per fruit)	Fruit dry weight (%)
S	0.52 ± 0.02a	0.51 ± 0.02b	10.88 ± 0.62b	8.93 ± 0.02b
SF	0.66 ± 0.07a	0.65 ± 0.05a	15.00 ± 1.39a	9.94 ± 0.32a
SFS	0.56 ± 0.04a	0.54 ± 0.04ab	12.63 ± 1.25ab	8.90 ± 0.11b
OF	0.25 ± 0.05b	0.22 ± 0.05c	8.90 ± 1.85b	8.70 ± 0.11b
P value	***	***	*	**
$LSD_{0.05}$	0.15	0.14	3.78	0.58

Values are mean ± SE ($n = 6$), and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means followed by the same letter in the same column do not differ significantly. Levels of significance are represented by $^{*}P < 0.05$, $^{**}P < 0.01$ and $^{***}P < 0.001$.
[a] S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field.

The total yield did not differ significantly between treatments under the screen (S, SF and SFS) and was about 62% higher than that of the OF treatment (Table 2). The highest commercial yield corresponded to the SF treatment, being twofold higher than that of the OF treatment (Table 2). The average fruit weight was higher in the treatments with fogging (SF and SFS), with fruits weighing up to 4 g more than OF fruits (Table 2). The fruit dry weight peaked in the SF treatment, with a value 14% higher than that in the OF treatment (Table 2).

Effects of environmental conditions on quality parameters

The concentrations of antioxidant components such as vitamin C and carotenoids (lycopene, β-carotene and lutein) were measured in tomato fruits (Fig. 1). The vitamin C content peaked in OF fruits (225 µg mg^{-1} FW), while S and SFS fruits showed the lowest values, with reductions of 39 and 42% respectively (Fig. 1A).

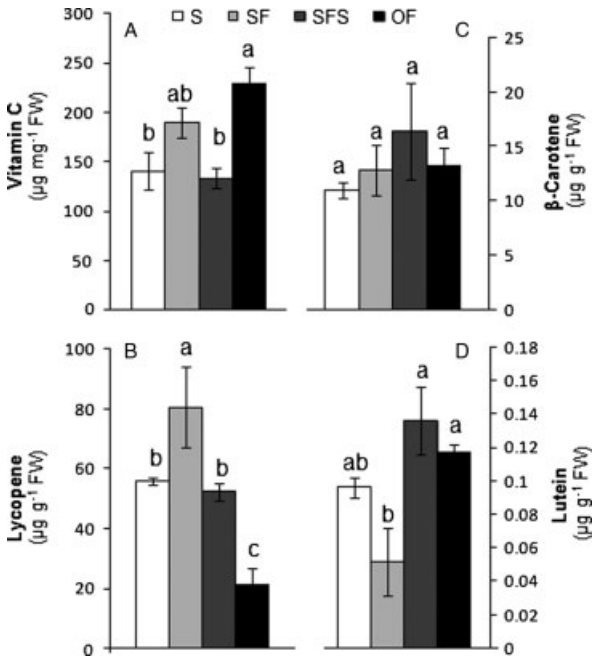

Figure 1. Effects of different environmental conditions on (A) vitamin C, (B) lycopene, (C) β-carotene and (D) lutein contents in tomato fruit extracts: S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field. Values are mean ± SE ($n = 9$) and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means with the same letter do not differ significantly.

The lycopene concentration was threefold higher (73%) in SF fruits than in OF fruits, which showed the lowest value (Fig. 1B). The concentration of β-carotene did not differ significantly between treatments (Fig. 1C). On the other hand, the concentration of lutein was highest in SFS and OF fruits, showing an increase of about 64% over that in SF fruits (Fig. 1D).

The content of flavonoids and glycosides (Table 3) was higher in OF fruits than in screenhouse (S, SF and SFS) fruits. In the case of hydroxycinnamic acids and derivatives, OF fruits showed a 22% higher content than S and SF fruits (Table 3). The total phenol content was highest in OF fruits, being up to 31% higher than in S and SF fruits (Table 3).

The antioxidant capacity was evaluated by FRAP (Fig. 2A), TEAC (Fig. 2B), reducing power (Fig. 2C) and DPPH (Fig. 2D) measurements. The S treatment showed the lowest values for all parameters, while the SF and OF treatments presented the highest values.

Sugars and organic acids are important in the metabolic response and determine the organoleptic properties of fruits and fruit juices. The concentration of fructose in tomato fruits peaked in the S and OF treatments, with values 41 and 54% higher than those in the SF and SFS treatments respectively (Table 4). The glucose concentration was highest in S fruits and lowest in OF fruits (Table 4). However, the sucrose concentration did not show significant differences between treatments (Table 4).

Low-molecular-mass organic acids are involved in essential pathways in plant metabolism. For instance, citrate and malate are two intermediates in the Krebs cycle, the central energy-producing pathway of cells. In this study the organic acids quantified were citric acid and malic acid (Table 4). OF fruits showed the lowest levels of both organic acids, while the highest level of citric acid was reached in SF fruits and the highest level of malic acid in S and SF fruits (Table 4).

Figure 3 shows the influence of environmental differences on the sweetness index (Fig. 3A) and sugar/acid ratio (Fig. 3B) in cherry tomato fruits. The highest values for both parameters corresponded to the S and OF treatments.

DISCUSSION

The nutritional quality of vegetables for fresh consumption is a complex issue. The market value of vegetables tends to be based mostly on external qualities such as size, shape and colour, while important intrinsic qualities such as texture, smell, flavour and nutraceutical properties are often not considered.[34] In this study we sought to determine the yield and quality of cherry tomato

Table 3. Phenolic compound contents (mg g^{-1} dry weight) of tomato fruits under different environmental conditions

Treatment[a]	Flavonoids and glycosides	Hydroxycinnamic acids and derivatives	Others	Total
S	1.67 ± 0.10b	2.17 ± 0.04b	0.13 ± 0.005b	3.97 ± 0.14c
SF	1.58 ± 0.11b	2.14 ± 0.02b	0.13 ± 0.003b	3.85 ± 0.12c
SFS	1.89 ± 0.16b	2.59 ± 0.10a	0.13 ± 0.009b	4.61 ± 0.25b
OF	2.78 ± 0.06a	2.78 ± 0.11a	0.15 ± 0.002a	5.72 ± 0.08a
P value	***	**	*	***
$LSD_{0.05}$	0.38	0.2	0.01	0.49

Values are mean ± SE ($n = 9$), and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means followed by the same letter in the same column do not differ significantly. Levels of significance are represented by $^{*}P < 0.05$, $^{**}P < 0.01$ and $^{***}P < 0.001$.
[a] S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field.

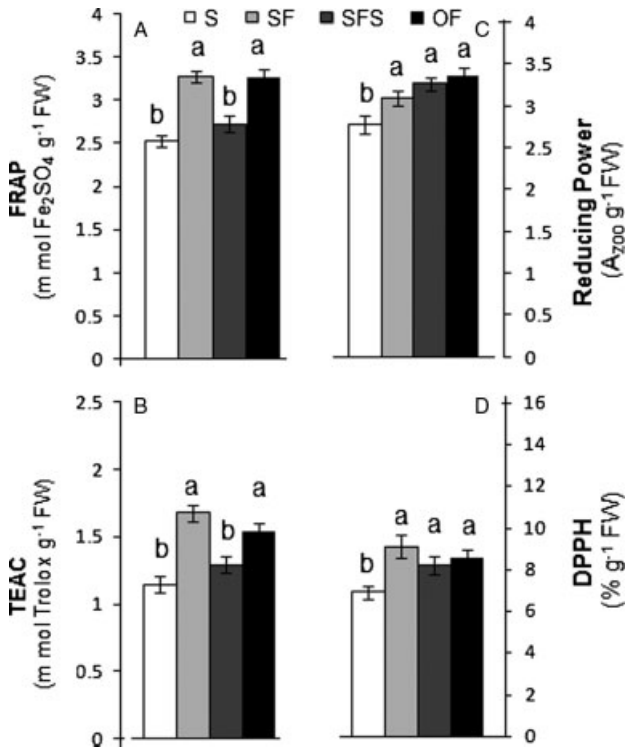

Figure 2. Effects of different environmental conditions on (A) FRAP, (B) TEAC, (C) reducing power and (D) DPPH measurements in tomato fruit extracts: S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field. Values are mean ± SE ($n = 9$) and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means with the same letter do not differ significantly.

fruits under different environmental conditions produced by a screenhouse, a fogging system and complementary devices such as plastic sheeting to maintain the microclimate created by the fogging system inside a screenhouse.

The production of high-quality crops requires the control of the main climatic factors such as light intensity, temperatures and VPD. A fogging system is usually used to relieve plants from high air temperatures and strong solar radiation during summer in the Mediterranean area,[24] chiefly by increasing the humidity. According to Bakker,[35] humidity is one of the most important environmental factors influencing the water status of greenhouse plants and consequently affects all processes that are associated with transpiration, e.g. water balance, transpiration cooling and ion translocation. Similarly, Leonardi *et al*.[36] demonstrated that higher VPD (2.2 kPa) intensified tomato fruit colour. In the SF treatment, air humidity enhancement by fogging by about 39%, with the VPD maintained around 3 kPa, boosted fruit weight by 32% per plant, resulting in the highest commercial production (Tables 1 and 2). However, although shading has been reported affect fruit yield by decreasing fruit weight,[21] this effect appeared to have been offset by fogging in our study, since the treatments with active environmental control (SF and SFS) reached the highest values of total and commercial yields and average fruit weight (Table 2). Similar results were found by El-Gizawy *et al*.,[37] who showed that greater shading of the tomato crop boosted total production by 50%. The reduced VPD in the SF and SFS treatments may affect fruit growth differently. The increase in fruit size and fruit dry weight in the SF treatment could be caused by an improvement in the source–sink relationship (or maybe reduced fruit transpiration due to climatic improvements), while the increase in fruit size in the SFS treatment was caused by an increase in water content promoted by the xylem water flux to fruits (Table 2).

The two best-known environmental factors influencing the nutritional value of tomato are light and temperature.[1] In this study, solar radiation in the treatments with a cooling system (SF and SFS) was reduced by more than 40% with respect to conditions reached outside (OF). Phytonutrients such as vitamin C, carotenoids and phenols in tomato are strongly affected by the intensity, duration and quality of light.[11] There appears to be a relationship between high vitamin C levels and relatively poor yields.[5] Our results showed an increase in the vitamin C content of fruits in the OF treatment (Fig. 1A), corroborating that light exposure is favourable to vitamin C accumulation in tomato fruits.[1] On the contrary, the low solar radiation experienced by plants in the S, SF and SFS treatments decreased the vitamin C concentration (Fig. 1A). These results are supported by El-Gizawy *et al*.,[37] who showed that the ascorbic acid content of open field tomato fruits decreased with increasing shade. The health-promoting benefits of tomatoes and tomato products have been attributed mostly to their significant lycopene content.[38] Results obtained by Raffo *et al*.[39] indicated that the hot mid-summer temperatures in the Mediterranean basin may have a significantly negative effect on lycopene accumulation. Cherry tomato fruits subjected to high temperatures and solar radiation showed an increase in lipid peroxidation and a decrease in the content of carotenoids such as lycopene.[40] The lycopene level in our study appeared to be influenced by solar radiation but not by high temperatures, as there was a 73% decline in the content of this phytonutrient in fruits of the OF treatment during high-radiation conditions (24.4 MJ m^{-2} day^{-1}) (Fig. 1B). Meanwhile, among

Table 4. Sugar and organic acid contents (mg g^{-1} fresh weight) of tomato fruits under different environmental conditions

Treatment[a]	Fructose	Glucose	Sucrose	Citric acid	Malic acid
S	0.87 ± 0.08a	1.40 ± 0.13a	1.08 ± 0.23	0.71 ± 0.05a	0.85 ± 0.01a
SF	0.53 ± 0.15ab	1.07 ± 0.19ab	1.28 ± 0.08	0.75 ± 0.04a	0.85 ± 0.01a
SFS	0.42 ± 0.14b	0.85 ± 0.14b	1.39 ± 0.09	0.70 ± 0.05ab	0.83 ± 0.02ab
OF	0.90 ± 0.15a	0.75 ± 0.08b	1.51 ± 0.24	0.58 ± 0.02b	0.78 ± 0.02b
P value	*	*	NS	*	*
$LSD_{0.05}$	0.4	0.42	0.52	0.13	0.05

[a] Values are mean ± SE ($n = 9$), and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means followed by the same letter in the same column do not differ significantly. Levels of significance are represented by $^*P < 0.05$ and NS (not significant), $P > 0.05$.

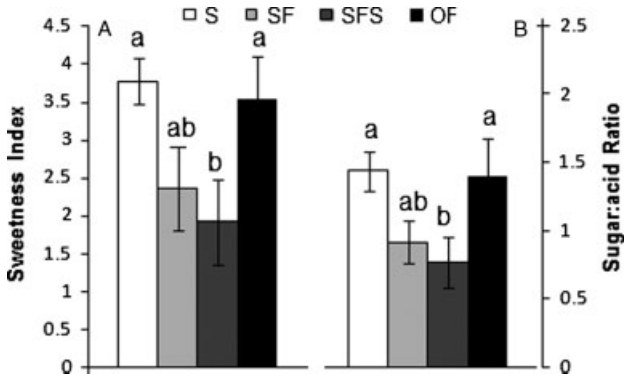

Figure 3. Effects of different environmental conditions on (A) sweetness index and (B) sugar/acid ratio in tomato fruit extracts: S, screenhouse; SF, screenhouse + fogging system; SFS, screenhouse + fogging system + plastic sheeting; OF, open field. Values are mean ± SE ($n = 9$) and differences between means were compared by Fisher's LSD test ($P = 0.05$). Means with the same letter do not differ significantly.

the screenhouse treatments, SFS fruits showed an intermediate lycopene concentration, even at temperatures higher than 32 °C (the temperature that inhibits the rate of lycopene synthesis).[41] The data from the OF treatment confirmed the findings of Andrews *et al.*,[42] who reported that lycopene accumulation was inversely related to a decrease in vitamin C content during fruit ripening. In this way, lycopene could replace depleted vitamin C as an antioxidant.[43]

Several studies report that temperatures above 30–35 °C and strong solar radiation stimulate lycopene oxidation to β-carotene.[1] Nevertheless, the β-carotene concentration showed no significant differences between treatments, implying that its accumulation may not have been due to the degradation of lycopene in the case of the screenhouse treatments (S, SF and SFS) (Fig. 1C). It has been reported that lutein prevents reactive oxygen species formation.[44] The SFS and OF treatments, which showed the highest temperature and solar radiation levels respectively, presented the highest values of lutein concentration (Fig. 1D).

The production of flavonoids and other phenylpropanoids may be stimulated to protect plant tissues from UV damage.[18] Fruits of the OF treatment, characterised by higher light intensity and the presence of UV-B radiation, indeed showed the highest flavonoid concentration (Table 3). Plants grown under intense light have been reported to have approximately twofold greater soluble phenol content than plants grown under dimmer light.[1] Our results demonstrated up to a 20% increase in the total phenol level of OF fruits compared with SFS, S and SF fruits. The plastic sheeting in the SFS treatment provided a diffusive cover, reducing the overall radiation while providing a more uniform spatial distribution of diffuse solar radiation inside the screenhouse.[45–47] This could explain why the values of the antioxidant contents (vitamin C, lycopene, lutein and phenolic compounds) were no lower than expected with respect to the OF and S treatments.

Several methods were used to determine the antioxidant capacity. The OF treatment showed the highest values in all tests (Fig. 2), indicating stronger antioxidant capacity due to the higher solar radiation and VPD, this coinciding with the increase in other antioxidant parameters such as vitamin C, flavonoids and total phenolic acids (Tables 1 and 3, Fig. 1A). On the other hand, the SF treatment also presented high values in all antioxidant tests (Fig. 2), in accordance with the increased content of lycopene (Fig. 1B), which is catalogued as fundamental in the final nutritional quality and commercial value of tomato fruits.[1]

The content of soluble sugars, measured as the concentrations of fructose and glucose, proved to be influenced by environmental conditions (Tables 1 and 4). The amount and intensity of light during the growing season influence the sugar content in fruits, because the ascorbic acid and flavonoids synthesised from them are supplied by photosynthesis.[11] OF fruits, with a positive correlation between the total sugar content and vitamin C and flavonoids, had the highest levels of phytonutrient compounds (Fig. 1A, Tables 3 and 4). Sugars, organic acids and their interactions are important components of sweetness, sourness and flavour intensity in tomatoes, thus acting as major determinants of tomato quality.[48] The glucose content was higher than the fructose content except in the OF treatment, where the reverse was true (Table 4). This fact positively affected the sweetness index in the OF treatment (Table 4, Fig. 3A), while the fogging treatments SF and SFS showed the lowest sweetness index because the stressful environmental conditions were alleviated (Fig. 3A, Table 1). The quality of fruits harvested during the hot summer is characterised by high titratable acidity.[27] The levels of malic acid were higher than those of citric acid in all tomato fruits, with OF fruits showing the lowest values for both organic acids (Table 4). The same dynamics found for the sweetness index (Fig. 3A) was also observed for the sugar/acid ratio (Fig. 3B). The OF and S treatments had the highest values and the fogging system treatments SF and SFS the lowest values.

CONCLUSIONS

Yield was associated with higher productivity (number of fruits produced per plant) and larger fruits. Screenhouse vegetable production offers advantages compared with production in the open field, especially under Mediterranean summer conditions. However, maximisation of biomass production does not

necessarily enhance product quality. It is necessary to find a balance between production and nutritional quality.

Tomato is among the most widely consumed vegetables worldwide and an important source of certain antioxidants, including lycopene, β-carotene and vitamin C. These substances are involved not only in plant defence but also in human health. Certainly, the health benefits of tomatoes have been attributed mostly to the significant amounts of lycopene they contain. Our results confirm that the low radiation and temperatures values of the SF treatment in summer in the Mediterranean basin may exert a significantly positive effect on lycopene accumulation. However, the OF treatment showed a possible relationship between high antioxidant concentration (vitamin C, flavonoids and total phenolic compounds) and extreme climatic factors such as solar radiation and VPD. Although SF and OF fruits showed the highest values of antioxidant capacity measured by several antioxidant tests, OF fruits presented the best values for organoleptic parameters (sweetness index and sugar/acid ratio).

In summary, for the production and nutritional parameters measured, we postulate that the SF treatment provides the best balance between production and nutritional quality in a summer Mediterranean cherry tomato crop.

ACKNOWLEDGEMENTS

This work was executed within the project INIA-RTA2009-0005, funded by the European Union through FEDER funds and the collaboration of the research group AGR161 (Plan Andaluz de Investigación, Junta de Andalucía).

REFERENCES

1 Dumas Y, Dadomo M, Di Lucca G and Grolier P, Effects of environmental factors and agricultural techniques on antioxidant content of tomatoes. *J Sci Food Agric* **83**:369–382 (2003).
2 Pieper JR and Barrett DM, Effects of organic and conventional production systems on quality and nutritional parameters of processing tomatoes. *J Sci Food Agric* **89**:177–194 (2009).
3 Schreiner M, Huyskens-Keil S, Krumbein A, Schonhof I and Linke M, Environmental effects on product quality, in *Fruit and Vegetable Quality*, ed. by Shewfelt RL and Brückner B. Technomic Publishing, Lancaster, PA, pp. 85–95 (2000).
4 George B, Kaur C, Khurdiya DS and Kapoor HC, Antioxidants in tomato (*Lycopersicon esculentum*) as a function of genotype. *Food Chem* **84**:45–51 (2004).
5 Stevens MA and Rick CM, Genetics and breeding, fruit quality, in *The Tomato Crop, a Scientific Basis for Improvement*, ed. by Atherton JG and Rudich J. Chapman and Hall, London, pp. 84–96 (1986).
6 Lenucci MS, Cadinu D, Taurino M, Piro G and Dalessandro G, Antioxidant composition in cherry and high-pigment tomato cultivars. *J Agric Food Chem* **54**:2606–2613 (2006).
7 Rao AVR and Agarwa S, Role of antioxidant lycopene in cancer and heart disease. *J Am Coll Nutr* **19**:563–569 (2000).
8 Voutilainen S, Nurmi T, Mursu J and Rissanen TH, Carotenoids and cardiovascular health. *Am J Clin Nutr* **83**:1265–1271 (2006).
9 Sesso HD, Carotenoids and cardiovascular disease: what research gaps remain? *Curr Opin Lipidol* **17**:11–16 (2006).
10 Engelmann NJ, Clinton SK and Erdman Jr JW, Nutritional aspects of phytoene and phytofluene, carotenoid precursors to lycopene. *Adv Nutr* **2**:51–61 (2011).
11 Dorais M, Ehret DL and Papadopoulos AP, Tomato (*Solanum lycopersicum*) health components: from the seed to the consumer. *Phytochem Rev* **7**:231–250 (2008).
12 Dorais M, Papadopoulus A and Gosselin A, Greenhouse tomato fruit quality. *Hort Rev* **26**:239–319 (2001).
13 Murneek AE, Maharg L and Witter SH, Ascorbic acid (vitamin C) content of tomatoes and apples. *Univ Missouri Agric Exp Sta Res Bull* **568**:3–24 (1954).
14 Liptay A, Papadopoulos AP, Bryan HH and Gull D, Ascorbic acid levels in tomato (*Lycopersicon esculentum* Mill) at low temperatures. *Agric Biol Chem* **50**:3185–3187 (1986).
15 Lopez-Andreu FJ, Lamela A, Esteban RM and Collado JG, Evolution of quality parameters in the maturation stage of tomato fruit. *Act Hort* **191**:387–394 (1986).
16 Davey MW, Montagu MV, Inze D, Sanmartin M, Kanellis A, Smirnoff N, *et al*., Plant L-ascorbic acid: chemistry, function, metabolism, bioavailability and effects of processing. *J Sci Food Agric* **80**:825–860 (2000).
17 Rosales MA, Cervilla LM, Sánchez-Rodríguez E, Rubio-Wilhelmi MM, Blasco B, Rios JJ, *et al*., The effect of environmental conditions on nutritional quality of cherry tomato fruits: evaluation of two experimental Mediterranean greenhouses. *J Sci Food Agric* **91**:152–162 (2011).
18 Dixon RA and Paiva NL, Stress-induced phenylpropanoid metabolism. *Plant Cell* **7**:1085–1097 (1995).
19 Brandt K, Giannini A and Lercari B, Photomorphogenic responses to UV radiation. III: A comparative study of UVB effects on anthocyanin and flavonoid accumulation in wild-type and *aurea* mutant of tomato (*Lycopersicon esculentum* Mill.). *Photochem Photobiol* **62**:1081–1087 (1995).
20 Migliori C, Di Cesare LF, Lo Scalzo L, Campanelli G and Ferrari V, Effects of organic farming and genotype on alimentary and nutraceutical parameters in tomato fruits. *J Sci Food Agric* **92**:2833–2839 (2012). DOI: 10.1002/jsfa.5602.
21 Wada T, Ikeda H, Matsushita K, Kambara A, Hirai H and Abe K, Effects of shading in summer on yield and quality of tomatoes grown on a single-truss system. *J Jpn Soc Hort Sci* **75**:51–58 (2006).
22 Abdel-Ghany AM, Al-Helal IM, Alzahrani SM, Alsadon AA, Ali IM and Elleithy RM, Covering materials incorporating radiation-preventing techniques to meet greenhouse cooling challenges in arid regions: a review. *Sci World J* **2012**:1–11 (art. n° 906360) (2012). DOI:10.1100/2012/906360.
23 Kittas C, Rigakis N, Katsoulas N and Bartzanas T, Influence of shading screens on microclimate, growth and productivity of tomato. *Act Hort* **807**:97–102 (2009).
24 Romero-Gámez M, Suárez-Rey EM and Soriano T, Effects of misting used to improve the microclimate and productivity of a screenhouse crop. *Eur J Hort Sci* **77**:49–57 (2012).
25 Shahak Y, Gussakovsky EE, Gal E and Ganelevin R, ColorNets: crop protection and light-quality manipulation in one technology. *Act Hort* **659**:143–151 (2004).
26 Hejtmánková K, Pivec V, Trnková E, Hamouz K and Lachman J, Quality of coloured varieties of potatoes. *Czech J Food Sci* **27**:310–313 (2009).
27 Sérino S, Gomez L, Costagliola G and Gautier H, HPLC assay of tomato carotenoids: validation of a rapid microextraction technique. *J Agric Food Chem* **57**:8753–8760 (2009).
28 Sánchez-Rodríguez E, Ruiz JM, Ferreres F and Moreno DA, Phenolic profiles of cherry tomatoes as influenced by hydric stress and rootstock technique. *Food Chem* **134**:775–782 (2012).
29 Benzie UEF and Strain JJ, The ferric ability of plasma (FRAP) as a measure of antioxidant power: the FRAP assay. *Ann Biochem* **239**:70–76 (1996).
30 Cai Y, Luo Q, Sun M and Corke H, Antioxidant activity and phenolic compounds of 112 traditional Chinese medicinal plants associated with anticancer. *Life Sci* **74**:2157–2184 (2004).
31 Hsu CL, Chen W, Weng YM and Tseng CY, Chemical composition, physical properties, and antioxidant activities of yam flours as affected by different drying methods. *Food Chem* **83**:85–92 (2003).
32 Keutgen AJ and Pawelzik E, Quality and nutritional value of strawberry fruit under long term salt stress. *Food Chem* **107**:1413–1420 (2008).
33 Mencarelly F and Salveit ME, Ripening of mature-green tomato fruit slices. *J Am Soc Hort Sci* **113**:742–745 (1988).
34 Gruda N, Impact of environmental factors on product quality of greenhouse vegetables for fresh consumption. *Crit Rev Plant Sci* **24**:227–247 (2005).
35 Bakker JC, Physiological disorders in cucumber under high humidity conditions and low ventilation rates in greenhouses. *Act Hort* **156**:257–264 (1984).
36 Leonardi C, Guichards S and Bertini N, High vapour pressure deficit influences growth, transpiration and quality of tomato fruits. *Sci Hort* **84**:285–296 (2000).

37 El-Gizawy AM, Abdallah MMF, Gomaa HM and Mohamed SS, Effect of different shading levels on tomato plants. 2. Yield and fruit quality. *Acta Hort* **323**:349–354 (1993).
38 Ilicć ZS, Milenkovicć L, Stanojevicć L, Cvetkovicć D and Fallik E, Effects of the modification of light intensity by color shade nets on yield and quality of tomato fruits. *Sci Hort* **139**:90–95 (2012).
39 Raffo A, La Malfa G, Fogliano V, Maiani G and Quaglia G, Seasonal variations in antioxidant components of cherry tomatoes (*Lycopersicon esculentum* cv. Naomi F1). *J Food Compos Anal* **19**:11–19 (2006).
40 Rosales MA, Ruiz JM, Hernández, J, Soriano T, Castilla N and Romero L, Antioxidant content and ascorbate metabolism in cherry tomato exocarp in relation to temperature and solar radiation. *J Sci Food Agric* **86**:1545–1551 (2006).
41 Grierson D and Kader AA, Fruit ripening and quality, physiology and biochemistry of ripening, in *The Tomato Crop, a Scientific Basis for Improvement*, ed. by Atherton JG and Rudich J. Chapman and Hall, London, pp. 241–259 (1986).
42 Andrews PK, Fahy DA and Foyer CH, Relationships between fruit exocarp antioxidants in the tomato (*Lycopersicum esculentum*) high pigment-1 mutant during development. *Physiol Plant* **120**:519–528 (2004).
43 Torres CA, Andrews PK and Davies NM, Physiological and biochemical responses of fruit exocarp of tomato (*Lycopersicum esculentum* Mill.) mutants to natural photo-oxidative conditions. *J Exp Bot* **57**:1933–1947 (2006).
44 Dall'Osto L, Lico C, Alric J, Giuliano G, Havaux M and Bassi R, Lutein is needed for efficient chlorophyll triplet quenching in the major LHCII antenna complex of higher plants and effective photoprotection *in vivo* under strong light. *BMC Plant Biol* **6**:32 (2006).
45 Healey KD, Hammer GL, Rickert KG and Bange MP, Radiation use efficiency increases when the diffuse component of incident radiation is enhanced under shade. *Aust J Agric Res* **49**:665–672 (1998).
46 Raveh E, Cohen S, Raz T, Grava A and Goldschmidt EE, Increased growth of young citrus trees under reduced radiation load in a semi-arid climate. *J Exp Bot* **54**: 365–373 (2003).
47 Lee SK and Kader AA, Preharvest and postharvest factors influencing vitamin C content of horticultural crops. *Postharvest Biol and Technol* **20**:207–220 (2012).
48 Helyes L, Dimény J, Pék Z and Lugasi A, Effect of variety and growing methods as well as cultivation conditions in the composition of tomato (*Lycopersicon lycopersicum* (L.) karsten) fruit. *Act Hort* **712**:511–516 (2006).

