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Storage under combined ultraviolet (UV) and light-emitting diodes (LED) enhances carotenoid concentration in mature green tomatoes

C. Cano-Molina, A. López-Fernández, N. Díaz-González, R. González-Barrio, N. Baenas, M.J. Periago and F.J. García-Alonso*

Department of Food Science and Nutrition, Veterinary Faculty, University of Murcia, Campus de Espinardo 30100, Murcia, Spain

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ABSTRACT

Tomato is rich in different bioactive compounds, especially the carotenoid lycopene, which intake is associated with various health benefits. Post-harvest use of ultraviolet light (UV) and light-emitting diode (LED) has been shown to increase the concentration of tomato bioactive compounds. The aim of this study was to evaluate the effect of ultraviolet (A and C) and red-blue LED light on the concentration of carotenoids during a 7-days storage trial of mature green tomatoes. Exposure to combined UV and LED light nearly doubled the total carotenoid concentration and had no negative impact on sensory attributes.

KEYWORDS

tomato, light-emitting diodes, carotenoids, post-harvest, ultraviolet, lycopene

1. INTRODUCTION

Intake of carotenoids has been correlated with the reduced incidence of several chronic diseases, including type 2 diabetes, cardiovascular diseases, and several types of cancer (Böhm et al., 2020). Tomato (*Solanum lycopersicum* L.) is a source of bioactive phytochemicals as lycopene,

* Corresponding author. Tel.: +34 868 889643; fax: +34 868 884147. E-mail: fjgarcia@um.es

ascorbic acid, tocopherol, and phenolic compounds (Chaudhary et al., 2018). Tomato is a climacteric fruit and continues to ripen after harvest, therefore, leaving room for further biosynthesis of bioactive compounds. Various strategies have been developed to increase the concentration of bioactive compounds during post-harvest storage. Among them, artificial lighting treatments using ultraviolet light (UV) and/or light-emitting diodes (LED) have been shown to enhance carotenoid levels (Bravo et al., 2012; Nájera et al., 2018; Panjai et al., 2017, 2019; Dyshlyuk et al., 2020). The aim of the present study was to evaluate the effect of combined exposure to UV (A and C) and red-blue LED light on the concentration of carotenoids during storage of mature green tomatoes. Attention has been also paid to other quality parameters such as mass loss, colour, acidity, soluble solids, and sensory attributes.

2. MATERIALS AND METHODS

2.1. Samples and experimental design

Tomatoes (*S. lycopersicum* L.) cultivar "Asurcado" – belonging to the same batch – were purchased at the green stage of maturity 1 (USDA, 2005). Tomatoes were washed, weighed, and randomly assigned to each experimental condition ($n = 4$ tomatoes/condition). Tomatoes, with or without pre-treatment with combined UV (A+C) light, were stored for 7 days at room temperature (20 ± 1 °C; 63 ± 3% relative humidity) in the dark or under continuous red-blue LED (Fig. 1).

2.2. UV-light pre-treatment

The UV-light pre-treatment (1 kJ m^{-2}) was performed at room temperature in an UV-viewing cabinet (Panreac, Barcelona, Spain) equipped with two 8 W lamps emitting UVA ($\lambda = 366$ nm) and UVC ($\lambda = 254$ nm) (Bravo et al., 2012). Light intensity in the treatment area (40 Lux) was measured using a digital light meter (ISO-TECH LUX 1335, RS Amidata S.A., Madrid, Spain).

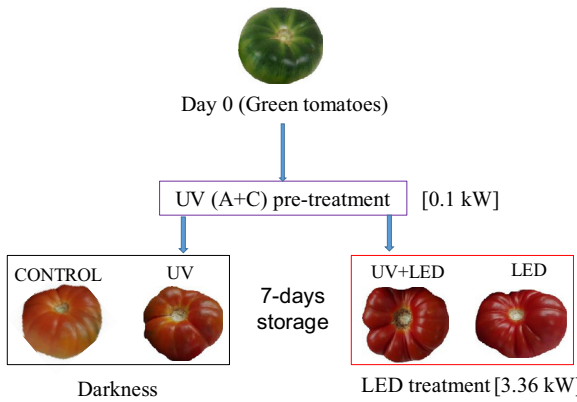

Fig. 1. Light conditions used for the storage of tomatoes. Energy consumption [kW] of each light treatment is shown between brackets

The full pre-treatment lasted 5 h and tomatoes were turned over after 2.5 h to ensure UV light exposure of both fruit sides.

2.3. Continuous red-blue LED storage

LED storage was carried out using a 24 W LED lamp (Light K5, Kmashi, WNT-Luxtech Co., Ltd. Guangdong, China) equipped with 9 red diodes (λ = 620–625 nm) and 3 blue diodes (λ = 460–467 nm). In order to ensure light exposure of both fruit sides, tomatoes were turned over daily. Light intensity in the treatment area was 3.7 kLux. Photosynthetic photon flux density (PPDF) (25.4 µmol m^{-2} s^{-1}) was measured using a spectrometer ALP-01 (Asensetek Incorporation, New Tai Pai City, Taiwan). Data of energy consumption of the different light conditions were measured using a Wi-Fi smart plug with energy monitoring EG-EW003MC (Energeeks Iberia S.L., Madrid, Spain). At the end of the storage trial, samples were homogenised and kept frozen at –20 °C until analysed. Green tomato samples (n = 4) were also analysed as initial control (day 0).

2.4. Analysis of carotenoids

Carotenoids were HPLC-analysed after extraction with methanol/tetrahydrofuran (v/v, 50:50) containing 0.1% butylated hydroxytoluene (Seybold et al., 2004). Chromatography separation was performed using a C30 column 250 × 4.6 mm, 5 µm i.d. (Análisis Vínicos S.L., Villarrobledo, Spain) in an Agilent HPLC system. Carotenoids were identified according to their absorption spectrum and retention times by chromatographic comparisons with authentic standards (Sigma, St. Louis, USA). Results were expressed as mg kg^{-1} of fresh mass.

2.5. Colour measurements and ripening index

Colour (CIELab) was measured in homogenised tomato samples using a colorimeter (Chroma meter CR300, Konica-Minolta, Tokio, Japan) and reported as L^*, a^*, and b^*, *Chroma* and *Hue* values. Colour index was calculated as the a^*/b^* ratio (Nájera et al., 2018). The total colour difference (ΔE) was used to characterise the overall change in colour during storage and was calculated by the following equation (Song et al., 2017):

$$\Delta E^*_{ab} = \sqrt{\left(L^*_2 - L^*_1\right)^2 + \left(a^*_2 - a^*_1\right)^2 + \left(b^*_2 - b^*_1\right)^2}$$

where L_1, a_1 and b_1 are L^* a^* b^* values of green tomatoes at day 0 (initial control).

The ripening index was calculated as the TSS to TA ratio (Majidi et al., 2011). The percent of total soluble solids (TSS) was measured at 20 °C using an Abbe Mat 200 digital refractometer (Anton Paar GmbH, Ostfildern, Germany). Titratable acidity (TA), expressed as citric acid (%), was determined by titrating with NaOH (0.1 N) up to pH 8.1.

2.6. Sensory analyses

To study the impact of light treatments on sensory attributes, the experiment was repeated with the most effective light condition (UV+LED) and the control. A Quantitative Descriptive Analysis (QDA) was carried out by 7 panellists trained according to ISO 8586:2012. The samples were randomly blind-labelled with 3 digit codes. The evaluated attributes were: peel colour, flesh

Table 1. References and descriptors for the quantitative descriptive analysis (QDA)

Sensory attribute/ Intensity	Low	Medium	High
Colour	Green tomato	Pink tomato	Red tomato
Firmness	Canned asparagus tip	Watermelon	Olives
Texture	Boiled courgette	Raw courgette	Raw carrot
Juiciness	Green apple	Orange	Watermelon
Sweetness	Water	Glucose (10 g L^{-1})	Glucose (20 g $L^{-}1$)
Acidity	Water	Citric acid (1.5 g L^{-1})	Citric acid (3 g L^{-1})
Odour	Unripe, grassy	Tomato-like, floral	Overripe, pungent, fermented
Taste	Unripe, leafy	Tomato-like, fruity, sweet	Overripe, pungent, fermented

colour, odour, texture, firmness, juiciness, sweetness, acidity, and taste. The intensity of each attribute was rated using an unstructured scale with defined boundaries, established using reference samples corresponding to different levels of intensity (low to high), and descriptors (Table 1). Panellists rated the samples on a 10 cm unstructured linear scale with anchor points at each end (0: low and 10: high).

2.7. Statistical analyses

Results are expressed as mean ± SD. Data were analysed by SPSS 24.0 (IBM, New York, USA). Comparisons between the means were analysed by one-way analysis of variance (ANOVA) followed by Tukey's test, whereas a Student's *T*-test was performed for sensory analyses. *P* values <0.05 were considered statistically significant.

3. RESULTS AND DISCUSSION

3.1. Carotenoids concentrations

Light conditions had significant impact on lycopene and β-carotene concentrations, but not on those of lutein (Table 2). Exposure to UV alone increased the carotenoid concentration in samples stored in darkness, but higher increases were observed in samples stored under continuous red-blue LED light. The strongest enhancing effect was observed for the combined UV+LED treatment, which significantly raised the total carotenoid concentration by 1.8-fold. In line with our results, in tomatoes stored at room temperature under continuous red light combined with full UV spectra short-daily treatments (30 min), a 1.5-fold increase in carotenoid concentration was documented, but the yield was similar to that elicited by red light alone (Panjai et al., 2017). In our study, the combined UV+LED treatment raised lycopene concentration by 1.7-fold and β-carotene concentration by 3.5-fold, when compared with control. This agrees with results of Panjai et al. (2017, 2019), who reported that β-carotene reached its maximum concentration after 10 days of storage under LED light alone or combined with UV, and then dropped. Instead, lycopene concentration continued to increase, while control

Table 2. Carotenoids, titratable acidity (TA), total soluble solids (TSS), ripening index (TA/TSS ratio), and mass loss of tomatoes stored under various light conditions

Light condition	Lutein (mg kg^{-1})	β-carotene (mg kg^{-1})	Lycopene (mg kg^{-1})	Total carotenoids[1] (mg kg^{-1})	TA (% citric acid)	TSS (%)	TSS/TA ratio	Mass loss (%)
Day 0								
Green tomato	1.62 ± 0.36^{a}	0.90 ± 0.40^{c}	Not detected	2.52 ± 0.76^{c}	0.77 ± 0.06^{a}	8.0 ± 0.3^{b}	10.4 ± 0.4^{b}	–
Day 7								
Control	1.18 ± 0.03^{a}	5.61 ± 0.06^{c}	77.50 ± 8.26^{c}	84.29 ± 8.35^{b}	0.72 ± 0.01^{a}	9.7 ± 0.4^{a}	13.6 ± 0.5^{a}	10.7 ± 2.1^{a}
UV	0.98 ± 0.12^{a}	11.99 ± 2.30^{b}	84.04 ± 12.35^{bc}	97.01 ± 14.77^{b}	0.70 ± 0.01^{a}	10.0 ± 0.4^{a}	14.4 ± 0.6^{a}	10.3 ± 2.5^{a}
LED	1.57 ± 0.25^{a}	17.47 ± 1.49^{a}	106.54 ± 6.29^{ab}	125.58 ± 8.03^{a}	0.63 ± 0.04^{a}	10.0 ± 0.4^{a}	15.8 ± 0.7^{a}	12.6 ± 2.6^{a}
UV + LED	1.40 ± 0.07^{a}	19.61 ± 0.18^{a}	132.32 ± 13.21^{a}	153.32 ± 13.44^{a}	0.64 ± 0.05^{a}	9.9 ± 0.3^{a}	15.6 ± 0.7^{a}	13.8 ± 2.5^{a}

[1]Total carotenoids were calculated as the sum of lutein, β-carotene, and lycopene.
[a–c] Different superscript letters within columns mean statistically significant differences at $P < 0.05$.

Table 3. Colour parameters of tomatoes stored under various light conditions

Light condition	L^*	a^*	b^*	*Colour index* (a^*/b^*)	*Chroma*	*Hue*	ΔE
Day 0							
Green tomato	51.38 ± 1.67^{a}	-9.63 ± 1.44^{c}	24.33 ± 1.43^{a}	-0.40 ± 0.04^{d}	26.17 ± 1.86^{a}	111.53 ± 1.79^{a}	–
Day 7							
Control	37.95 ± 0.19^{b}	18.48 ± 0.76^{b}	15.38 ± 0.96^{b}	1.20 ± 0.03^{c}	24.04 ± 1.20^{a}	39.77 ± 0.59^{b}	32.45 ± 0.49^{b}
UV	39.00 ± 2.82^{ab}	18.85 ± 0.52^{ab}	15.09 ± 0.52^{b}	1.25 ± 0.01^{c}	24.15 ± 0.74^{a}	38.69 ± 0.19^{bc}	32.45 ± 1.34^{b}
LED	36.66 ± 2.06^{b}	18.12 ± 1.00^{b}	13.20 ± 0.44^{b}	1.37 ± 0.03^{b}	22.45 ± 1.08^{a}	36.10 ± 0.60^{c}	33.25 ± 1.63^{ab}
UV + LED	35.19 ± 0.71^{b}	22.10 ± 0.43^{a}	13.39 ± 0.12^{b}	1.65 ± 0.01^{a}	25.84 ± 0.63^{a}	31.21 ± 0.22^{d}	37.30 ± 0.38^{a}

[a–d] Different superscript letters within columns mean statistically significant differences at $P < 0.05$.

tomatoes stored in darkness showed a delayed increase in both lycopene and β-carotene concentrations until day 10, and then rose. This could explain why, in our study, β-carotene concentration increased more strongly than of lycopene. At the end of our 7-day storage trial, the lowest β-carotene concentrations in control tomatoes and nearly the highest concentrations in treated tomatoes were measured.

3.2. Quality parameters: colour, TSS/TA ratio, and mass loss

As tomatoes ripened and carotenoid contents increased, colour parameters shifted to more reddish values, again more markedly following combined UV+LED treatment (Table 3). Compared with control, combined UV+LED treatment produced the highest changes in the a^* parameter (1.2-fold) and the colour index (a^*/b^*) (1.4-fold), indicating a shift towards red colour. Hue angle and lightness (L^*) dropped by about 70% and 30% in UV+LED samples, respectively, indicating the darkening of the red colour. Finally, the increase in the overall colour difference (ΔE) confirmed combined UV+LED treatment as majorly responsible for colour changes. As shown in Table 2, light treatments slightly increased the TSS/TA ratio due to increased TSS and reduced acidity (TA). This effect was more marked in tomatoes exposed to LED alone or in combination with UV. The pattern of changes observed for quality parameters agreed with previous reports (Panjai et al., 2017; Nájera et al., 2018). Mass losses were higher, albeit non-significantly, under LED illumination conditions (Table 2).

3.3. Sensory attributes

A second experiment was carried out to investigate whether the effect of UV+LED treatments were reproducible, as well as to assess the impact of light treatments on sensory attributes. As can be seen from Table 4, the second experiment gave similar results to the previous one; lycopene concentration increased 3-fold in samples exposed to UV+LED, and, consequently, overall colour difference (ΔE) showed a similar behaviour. Accordingly, these changes had a significant effect on flesh colour as detected by panellists in the QDA. As illustrated in Fig. 2, for UV+LED tomatoes, the scores for flesh (7.9) and peel colour (8.5) were the highest among attributes, whilst acidity (3.2) was the lowest. The panellists could clearly see the difference in flesh colour between control (5.7) and UV+LED sample (8.5), rating higher the tomatoes that had developed a redder or darker red colour. Panellists reported UV+LED treated tomatoes as

Table 4. Colour difference (ΔE), titratable acidity (TA), total soluble solids (TSS), ripening index (TSS/TA ratio), and weight loss of tomatoes stored under darkness or UV+LED light conditions in experiment 2

Light condition	Lycopene[1] (mg kg^{-1})	ΔE	TA (% citric acid)	TSS (%)	TSS/TA ratio	Mass loss (%)
Day 0						
Green tomato	0.8 ± 0.7^{c}	–	0.66 ± 0.02^{a}	5.2 ± 0.1^{c}	7.9 ± 0.2^{b}	–
Day 7						
Control	26.7 ± 1.0^{b}	39.4 ± 1.6^{b}	0.70 ± 0.02^{a}	9.0 ± 0.2^{a}	12.8 ± 0.3^{a}	4.3 ± 0.4^{a}
UV + LED	79.2 ± 1.7^{a}	74.2 ± 1.9^{a}	0.51 ± 0.02^{a}	7.3 ± 0.4^{b}	14.4 ± 0.7^{a}	5.2 ± 0.5^{a}

$^{a–c}$ Different superscript letters within columns mean statistically significant differences at $P < 0.05$.
[1]Colorimetric determination of lycopene (Sharma and Le Maguer, 1996).

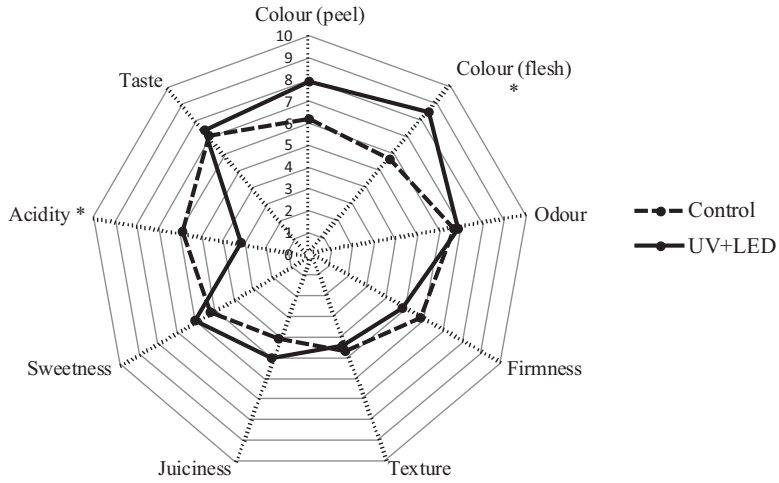

Fig. 2. Results of the quantitative descriptive analysis (QDA) of UV + LED and control tomatoes. The spider-web chart shows the mean sensory scores obtained for each attribute from the sensory evaluation. *Statistical significance at $P < 0.05$

less acid (3.2) than control (5.9), but they did not detect differences in sweetness. This is in line with the changes observed in the TSS/TA ratio – an indicator of fruit sweetness – that increased upon UV+LED treatment mainly due to decreased TA rather than to increased TSS (Table 4). Finally, no differences were observed for other sensory attributes such as juiciness, odour, taste, texture, or firmness. Again, mass loss was higher in UV+LED samples (Table 4), but it did not affect the perceived firmness and texture (Fig. 2).

4. CONCLUSIONS

Exposure to combined UV and LED light nearly doubled the total carotenoid concentration compared with tomatoes stored in the dark. Light treatments did not cause significant mass losses and had no negative impact on sensory attributes. Indeed, colour was improved and acidity reduced. LED light alone was sufficient to elicit a significant increase in carotenoid concentrations in comparison with combined UV and LED light. This can be considered an advantage, since it is not necessary to install UV lamps in addition to the safe and non-thermal LED lights to achieve an enhanced effect on carotenoid accumulation. Besides, LED lights are energy-efficient – our 7-days LED treatment consumed 3.36 kW in total – and might involve significant reductions in energy consumption compared to incandescent light, which consumes a minimum of 75% more energy (USDE, 2021). With regard to the relevance to local crop producers, one potential interest of supplemental lighting could be the management of temporary storage. For instance, when tomatoes are harvested at greener stages – e.g. harvested early to prevent freeze damage – artificial lighting could be a useful tool to foster ripening, improving commercial and antioxidant value, and thus, reducing the losses due to non-marketable production. Last but not least, LEDs are also suitable in cold-storage applications to increase tomato carotenoid contents (Baenas et al., 2021).

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