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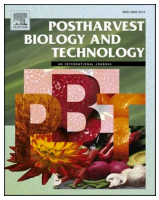

Potential application of pre-harvest LED interlighting to improve tomato quality and storability

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ABSTRACT

Growing conditions and agronomical inputs play a key role in determining fruit qualitative and nutraceutical traits at harvest and post-harvest. The hereby presented research investigated the effects of pre-harvest supplemental LED interlighting on post-harvest quality of hydroponically grown tomatoes (*Solanum lycopersicum* "Siranzo"). Three LED treatments, applied for 16 h d^{-1} (h 8.00–00.00), were added to natural sunlight and consisted of Red and Blue (RB), Red and Blue + Far-Red (FR), and Red and Blue + Far-Red at the end-of-day for 30 min (EOD), with an intensity of 180 μmol m^{-2} s^{-1} for Red and Blue, plus 44 μmol m^{-2} s^{-1} for Far-Red. A control treatment (CK), where plants were grown only with sunlight, was also considered. Fruits at red stage were selected and placed in a storage room at 13 °C in darkness. Fruit quality assessment was performed at harvest time and after one week of storage. RB and FR increased fruit firmness compared to CK, opening possible benefits toward reducing fruit losses during post-harvest handling. RB treated fruits also maintained a higher content of lycopene and β-carotene after the first week of storage. The study demonstrates that supplementary LED interlighting during greenhouse tomato cultivation may enhance storability and help preserve fruit nutritional properties during post-harvest.

1. Introduction

Post-harvest management is essential in maintaining tomato quality, ensuring long-term shelf-life, and reducing food waste from unsold and perishing products. Indeed, post-harvest losses of tomatoes can reach 25–40% of production (Khan and Jan, 2007), with economic consequences relapsing on farmers, the processing industry and traders (Kader et al., 1992). Cold storage, high carbon dioxide atmosphere, calcium chloride application and relative humidity control are some methods applied to reduce tomato's respiratory metabolisms and consequent food losses during post-harvest handling (Toor and Savage, 2006; Isaac et al., 2015). In particular, a storage temperature between 10 and 15 °C is the most applied for post-harvest preservation (Mata et al., 2019), being this the ideal temperature to ensure the long-term preservation of the fruit without impairing tomato flavor properties (Maul et al., 2000). Furthermore, storage temperatures lower than 13 °C can determine chilling injury, affecting tomato texture, surface pitting and fungal development (Mata et al., 2019).

Pre-harvest conditions and agricultural inputs are also crucial in determining fruit quality at harvest and post-harvest ripening (Isaac et al., 2015). For example, fertilizers may help prevent disease development (e.g., calcium) (Passam et al., 2007) or reduce ripening and color formation (e.g., nitrogen); flowers and fruit pruning help obtain an appropriate source/sink ratio and allow to increase fruit weight and dry matter content (Hanna, 2009); and correct irrigation management can increase sugar concentration in fruit (Mitchell et al., 1991). The maturity stage at which the fruit is harvested is another important pre-harvest factor that can influence post-harvest preservation. In particular, harvesting tomatoes at mature green stage can ensure a longer product shelf-life (Moneruzzaman et al., 2009), thanks to a lower sugar content that makes the fruit less vulnerable to mechanical damage (Toivonen, 2007). However, early harvests were also shown to reduce the nutritional and sensorial properties of the product (Balibrea et al., 2006; Isaac et al., 2015), with negative consequences on consumers' perception and

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nutritional value. Therefore, harvesting at mature-green stage can be advisable in case of product transportation at long distances while harvesting at red ripen stage is the best option for local consumption (Moneruzzaman et al., 2009; Isaac et al., 2015).

Light is a key factor in determining fruit quality being the main responsible for photosynthetic activity. In recent years, the development of highly efficient and low-cost light-emitting diodes (LEDs) has allowed the adoption of this technology for protected crop production (Paradiso and Proietti, 2021), fostering the study of how light manipulation may affect plant performances and fruit quality, particularly in tomatoes (Appolloni et al., 2021). Furthermore, LED light has also been applied to harvested tomatoes during storage to enhance berry quality and storage (Cozmuta et al., 2016; Ngcobo et al., 2021). Chlorophylls absorption peaks correspond to the Blue and Red spectral regions, and, therefore, several studies focused on the effect of Red and Blue lights on crop yield and quality (Kataoka et al., 2003; Li and Kubota, 2009; Pennisi et al., 2019, 2020). Blue light strongly affects leaf expansion and stomatal opening and frequently promotes the development of a more efficient photosynthetic apparatus than Red light (Savvides et al., 2012; Miao et al., 2016). Red light promotes seed germination and growth and may enhance chlorophyll accumulation (Fan et al., 2013; Tiansawat and Dalling, 2013). In addition, the Red:Far-Red ratio controls plant architecture, germination and flowering, although with different responses depending on plant species and growing conditions (Demotes-Mainard et al., 2016). To the best of our knowledge, only minimal research has investigated the effects of LED light applied during cultivation on the post-harvest quality of tomato fruit (Affandi et al., 2020, 2021). However, supplemental LED light application may be an interesting pre-harvest factor influencing post-harvest quality to be evaluated, given the activation of photoreceptor responses affecting plant metabolism. Accordingly, the present research aims to evaluate the effects of pre-harvest supplemental LED light on post-harvest quality of greenhouse-grown tomatoes, considering commercial storage standards.

2. Materials and methods

2.1. Pre-harvest growing conditions

Tomato plants (*Solanum lycopersicum* L. 'Siranzo' Rijk Zwaan, The Netherlands) were cultivated in a commercial greenhouse located at Mezzolara di Budrio, Bologna, Italy (44°34'49" N, 11°31'54" E), using a high-wire hydroponic system (Paucek et al., 2020). Seedlings in rockwool cubes were transplanted in rock wool slabs (Grodan Vital, Roermond, Netherlands) on January 13, 2020. Plants were grown with a two-stem V-system with a planting density of 3.1 stems m^{-2}. The environmental conditions (temperature, relative humidity, solar radiation) were monitored daily during the entire growing period. A passive (lateral and top openings) and active (horizontal fan system) ventilation, as well as residual hot water flowing in tubes coming from an adjacent biogas system, were used to maintain the proper climatic conditions (T_{max} 37 °C - T_{min} 11 °C; RH_{max} 97% – RH_{min} 36%). A computer-controlled drip-irrigation system managed fertigation, maintaining the nutrient solution at average pH= 6.0 and 2.6 dS m^{-1} average electrical conductivity (EC). The nutritive solution adopted by the commercial greenhouse is reported in Table S1. The supplemental lighting was provided by a single LED interlighting lamps (Flygrow Interlight, Flytech LED Technology, Belluno, Italy), located at 30 cm of distance from the stem, at the height of 1.40 cm from the rock wool slabs throughout the whole growing period. Three different lighting regimes were applied:

1) Red (660 nm) and Blue (465 nm) light with a Red:Blue ratio (R:B) of 3, a photosynthetic photon flux density (PPFD) of 180 μmol m^{-2} s^{-1} (measured at 30 cm from the plant) and a photoperiod of 16 h d^{-1} (8.00–00.00) (namely RB);.

2) RB treatment with an addition of 44 μmol m^{-2} s^{-1} of Far-Red light (730 nm) during the whole photoperiod (namely FR);.

3) RB treatment with an addition of 44 μmol m^{-2} s^{-1} of Far-Red, applied only for 30 min right after the 16 h d^{-1} of RB treatment (end-of-day) (namely EOD).

Peak wavelengths of emitted spectrum are reported in Fig. S1. Control plants (CK) grown under natural light were also considered. Lighting treatments were applied only for the final phase of the productive farm cycle, from August until November 2020. A randomized block design was used with three blocks containing 7 plants per treatment (21 plants per treatment in total) (Fig. S2).

2.2. Post-harvest preservation

Trusses at equal development stage were harvested from each plant. Afterward, fruit at red-mature stage and of the same size were selected among the harvested trusses. The fruit's red-mature ripening level was estimated by using a portable DA-Meter (DA-Meter, SINTELEIA srl, Bologna, Italy) (Rahman et al., 2019). DA-Meter is a portable device based on visible/Near Infra-Red (vis/NIR) spectroscopy developed to non-destructively assess fruit maturity (Farneti et al., 2015). Tomato fruits were selected for a uniform maturation red-ripe stage corresponding to a DA-index (I_{AD}) between 1.50 and 1.90. After the selection, tomatoes were immediately washed with sodium hypochlorite and stored in the dark at 13 °C, with 80% relative humidity, for 7 days. The duration of storage was established based on the standard applied by the commercial greenhouse that furnished the tomatoes.

2.3. Weight loss and hardness

Weight loss was calculated on 6 fruits per treatment per block as the difference between the weight of the fruit at the beginning of storage (T0) and their final weight after 7 d of storage (T7) divided by the T0. To normalize data, weight loss values were expressed as % of the initial value. On the same fruits in the same days, fruit hardness was evaluated using a Durofel device (Giraud Technologies, Cavaillon, France) (Planton, 1991), fitted with a 0.10 cm^2 probe, on four opposite sides of the equatorial diameter of each fruit per time point. The instrument non-destructively measured the elasticity of fruit exocarp, expressing it in a Durofel Index ranging from 0 to 100.

2.4. Color determination

Color was evaluated on 6 fruits per treatment per block at T0 and T7 on the same fruit by using a CIE Lab color space analysis, where L* component represents the lightness from black (0) to white (100), a* component is a value ranging from green (−) to red (+), and b* component is a value ranging blue (−) to yellow (+). A colorimeter (Chroma Meter CR-400, Minolta, Tokyo, Japan) was used to assess the values. The measures were performed on four opposite sides at the equatorial diameter fruit level. Two indexes, HUE angle (h) and Chroma (C), were deduced from a* and b* components applying the formulas $\tan^{-1}(b^*/a^*)^2$ and $(a^{*2} + b^{*2})^{0.5}$, respectively (Lopez Camelo and Gomez, 1998).

2.5. Destructive measurements for fruit quality evaluation

Destructive measurements were performed on 6 fruits per treatment per block, other than those of non-destructive measurements, and included pulp firmness, soluble solids content and titratable acidity evaluation. Pulp firmness was determined using a fruit texture analyzer (FTA GÜSS, Strand, South Africa), evaluating the force required to penetrate the fruit. The penetration was performed with a cylindrical and flat-end probe of 6 mm of diameter, with a depth equal to 11 mm and a speed of 30 mm s^{-1}. Measurements were performed on four opposite sides of the equatorial diameter, peeling the fruit before penetration. Soluble solids content was evaluated on each centrifuged fruit using a digital refractometer model PAL-1 (Atago Co., Ltd., Tokyo,

Japan). Titratable acidity was measured with an automatic TitroMatic (Compact-S titrator, Crison, Modena, Italy), diluting 20 mL of tomato juice in 20 mL of distilled water. The titratable acidity was estimated by titrating with 0.1 N NaOH until the titration end-point of pH 8.1.

2.6. Total polyphenols and total antioxidant capacity

Total polyphenols and total antioxidant capacity were analyzed on 4 tomatoes per treatment per block, other than those of non-destructive measurements. At T0 and T7, fruit samples were immersed in liquid nitrogen and kept at − 80 °C for analysis. Samples of 4 g of homogenized freeze-dried fruit were placed in tubes and 8 mL of extraction mixture (60% methanol, 30% H_2O, 10% acetone) were added (Hartmann et al., 2008). The extraction was carried out by centrifugation at 1677 g for 10 min at 4 °C. The supernatant was collected and used for antioxidant and total phenols analysis.

Total antioxidant capacity was analyzed using the FRAP (Ferric Reducing Antioxidant Power) method, developed following the method described by Benzie and Strain (1999), applying slight modifications. A reaction mixture containing acetate buffer (pH 3.6), 300 mM, 2,4,6-Tris (2-pyridyl)-s-triazine (TPTZ) solution (in 40 mM HCl) and 20 mM $FeCl_3$ was prepared in a v:v:v proportion of 10:1:1 and incubated for 2 h in darkness. Then, 1.2 mL of the reaction mixture was added to 20 μL of supernatant and incubated for 1 h at room temperature in darkness. The antioxidant capacity was referred to a 0–2.5 mM $FeSO_4$ calibration curve. Samples and standards were read at 593 nm with a spectrophotometer (Biochrom Ltd, Cambridge, England).

Total polyphenols were determined using the methodology described by Waterhouse (2002), applying slight modifications. Briefly, 50 μL of the sample extract was added to 800 μL of Folin-Ciocalteu reagent diluted 1:15 (v:v) in H_2O. Gallic acid calibration standards up to 400 μg mL^{-1} were also included in the test. After an incubation of 5 min, samples and standards were added with 150 μL of 20% Na_2CO_3, incubated for 1 h at room temperature and then read at 765 nm with a spectrophotometer (Biochrom Ltd, Cambridge, England). Results of total phenols and antioxidant activity were expressed in gallic acid and Fe^{2+} equivalents, respectively, on a fresh weight basis.

2.7. Lycopene and β-carotene content

Lycopene and β-carotene contents were evaluated on 4 tomatoes per treatment per block, the same as total polyphenols and total antioxidant capacity measurement, using the methodology described by Anthon and Barrett (2006), applying slight modifications. An extraction solution was prepared by mixing hexane, acetone and ethanol in a v:v:v proportion of 2:1:1, plus 0.5 g L^{-1} of butylated hydroxytoluene. Briefly, 0.5 g of homogenized frozen sample, including exocarp and mesocarp, were mixed with 10 mL of extraction solution. The material was left in darkness for 30 min and then centrifuged at 2000 × *g* for 5 min. Finally, 1 mL of supernatant was read at 503 and 444 nm with a spectrophotometer (Biochrom Ltd, Cambridge, England).

The lycopene content was calculated using the following formula (Anthon and Barrett, 2006):

$$lycopene \quad \left(\frac{mg}{kg}\right) = \left(\frac{x}{y}\right) \quad \times \quad A_{503} \times 3.12,$$

where *x* is the volume of hexane phase (mL, see below), *y* the weight of the fruit tissue (g), A_{503} is the absorbance at 503 nm, and 3.12 is the extinction coefficient. *β*-carotene was calculated with the following equation (Anthon and Barrett, 2006):

$$\beta\text{-}carotene = (9.38 \quad \times A_{444} - 6.70 \quad \times A_{503}) \times 0.55 \quad \times 537 \quad \times \frac{V}{W},$$

where A_{444} is the absorbance at 444 nm, A_{503} is the absorbance at 503 nm, 0.55 is the ratio of the final hexane layer volume to the volume of mixed solvents added for hexane:acetone:ethanol (2:1:1), *V* is the volume of mixed solvents added and 537 (g mol^{-1}) is the molecular weights of lycopene and *β*-carotene.

2.8. Statistical analysis

Non-destructive measurements (weight loss, fruit hardness, color) were analyzed through a repeated measures one way-ANOVA. Destructive measurements (pulp firmness, soluble solids content and titratable acidity) and biochemical evaluations were analyzed through a one-way ANOVA, by comparing lighting regimes within the different time (T0 and T7). Tukey's test was used for means comparison. Data were analyzed by using SPSS software.

3. Results

No differences in weight loss (as % from initial fruit weight) were observed between lighting treatments (mean weight loss of 1.8%, Table 1). The evaluation of fruit exocarp hardness showed no differences among treatments at T0. However, CK fruits were softer after one week compared to RB and FR ones (Fig. 1**a**). The same trends were observed in flesh firmness evaluation, although no significant differences were observed among treatments at both measured times (T0 and T7) (Fig. 1**b**).

Evaluations of fruit color did not show any difference among treatments neither at harvest or after 7 days of storage (Table 1). Mean fruit values at T0 and T7 were respectively 24.1 and 22.3 (a*), 30.7 and 29.4 (b*), 41.8 and 40.6 (L*), 0.91 and 0.92 (h), 39.0 and 36.9 (C). Similarly, soluble solid content (average value T0: 4.2 and T7: 4%) and titratable acidity (average value of T0: 4.1 and T7: 3.4 g L^{-1}) were not significantly influenced by lighting treatments (Table 1).

Biochemical analysis showed no differences among treatments in the case of total phenols content (average value 28.2 and 25.9 mg GA eqs. 100 g^{-1}) and antioxidant activity (average values of 0.28 and 0.28 mmol Fe^{2+} eqs. 100 g^{-1}), at T0 and T7, respectively (Table 1). Instead, carotenoid analysis demonstrated a significantly lower level of lycopene and β-carotene in fruits grown with natural light only (CK) compared to fruits grown under RB light treatment, after one week of post-harvest storage (Fig. 2**a** and Fig. 2**b**).

4. Discussion

Weight loss is one of the main problems of quality reduction in horticultural products during post-harvest (Nassarawa et al., 2021). The reasons for weight loss of tomatoes during storage can be attributed to environmental conditions, such as fruit's dehydration (Fagundes et al., 2015), as well as to normal cellular metabolic processes such as transpiration and respiration (Abiso et al., 2015). In the present research, tomatoes grown under different LED light treatments (RB, FR and EOD) or under natural light only (CK) did not show any significant difference in weight loss during storage (Table 1). Unfortunately, few researchers have investigated the effects of pre-harvest LED light on tomato post-harvest quality, often without reporting the weight loss effect. In Affandi et al. (2020), Far-Red light added to a Red and Blue base illumination has been found effective in reducing the relative weight loss of tomatoes during storage. The reduction in weight losses caused by Far-Red addition was related to an increase in cuticular thickness leading to a reduced transpiration rate (Cozmuta et al.,2016). Interestingly, in our experiments, all light treatments applied during cultivation resulted in a higher fruit skin hardness after 7 d of storage, suggesting that supplementary LED light may have increased cuticle thickness. This hypothesis is further corroborated by the fact that light treatments influenced only skin hardness but not flesh firmness (Fig. 1). Light could affect skin hardness and flesh firmness differently, considering that the two instruments have different evaluation parameters. For example, by measuring the elasticity of the peel, Durofel index can be more

Table 1
Mean values ± SD of qualitative parameters not reporting statistical difference ($p < 0.05$) among treatments, at harvest (T0) and after one week of storage (T7).

	CK		RB		FR		EOD	
	T0	T7	T0	T7	T0	T7	T0	T7
Destructive analysis								
Soluble solids (%)	4.3 ± 0.3	3.9 ± 0.2	4.3 ± 0.2	4.1 ± 0.3	4.0 ± 0.3	4.0 ± 0.3	4.2 ± 0.1	4.1 ± 0.3
Acidity (g L^{-1})	3.9 ± 0.6	3.4 ± 0.3	4.3 ± 0.3	3.3 ± 0.3	4.1 ± 0.5	3.4 ± 0.4	4.2 ± 0.1	3.8 ± 0.2
Non-destructive analysis								
*L**	41.4 ± 0.8	40.4 ± 1.1	41.7 ± 0.6	40.3 ± 1.0	41.7 ± 1.8	40.8 ± 1.3	42.5 ± 1.3	40.9 ± 1.6
*a**	23.1 ± 0.7	21.0 ± 1.8	25.2 ± 1.6	23.5 ± 1.6	23.8 ± 1.6	22.3 ± 2	24.2 ± 1.9	22.4 ± 2.2
*b**	30.5 ± 0.9	28.5 ± 1.0	31.1 ± 0.9	30.2 ± 1.0	30.2 ± 1.5	28.8 ± 1.5	30.9 ± 1.7	30.0 ± 1.4
h	0.9 ± 0.02	0.9 ± 0.03	0.9 ± 0.02	0.9 ± 0.02	0.9 ± 0.01	0.9 ± 0.03	0.9 ± 0.03	0.9 ± 0.03
C	38.3 ± 0.9	35.4 ± 1.8	40.0 ± 1.6	38.3 ± 1.7	38.5 ± 2.1	36.5 ± 2.3	39.3 ± 2.3	37.4 ± 2.3
*Weight loss (%) **	2.2 ± 0.7		1.8 ± 0.9		1.6 ± 0.6		1.4 ± 1.4	
Biochemical analysis								
Phenols (GA 100 g^{-1})	29.0 ± 5.3	26.0 ± 2.8	24.9 ± 2.3	26.5 ± 1.5	32.19 ± 5.0	26.7 ± 2.3	26.0 ± 2.5	24.5 ± 2.2
Antioxidant activity (mmol Fe^{2+} 100 g^{-1})	0.3 ± 0.1	0.3 ± 0.4	0.2 ± 0.05	0.3 ± 0.02	0.3 ± 0.03	0.3 ± 0.03	0.3 ± 0.05	0.3 ± 0.05

*Considering the difference between T0 and T7

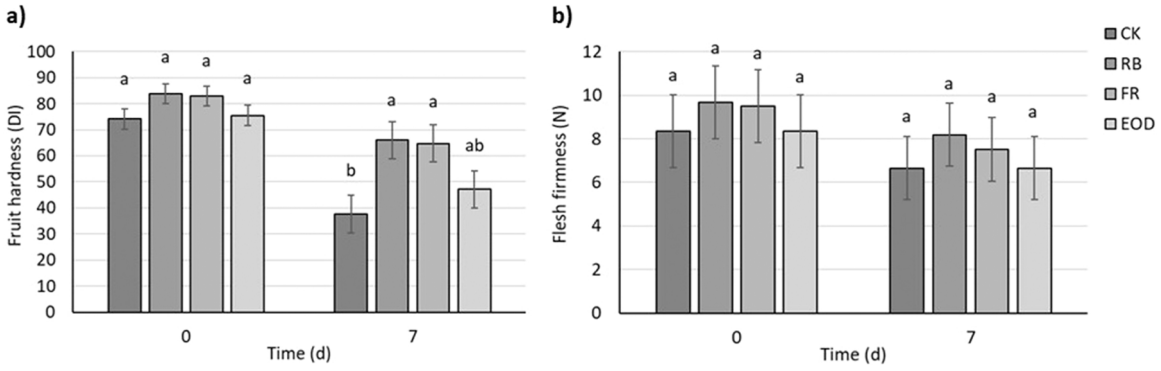

Fig. 1. a) Fruit hardness (Durofel Index, DI) after 0 and 7 d of storage ($p < 0.05$). **b)** Flesh firmness (N) after 0 and 7 d of storage ($p < 0.05$). In charts, vertical bars indicate SD, different letters indicate significant differences at $p < 0.05$.

influenced by the percentage fruit water content than the penetration evaluation.

The visual and sensorial parameters which have a more immediate effect on the consumers' perception and acceptance of the product are color, sweetness, acidity and consistency of the pulp. This research did not show any significant variation between treatments (Table 1), neither at the time of harvesting nor after one week of storage, in any of the commercial quality and organoleptic parameters described above. At the beginning of the storage, fruits used for the experiments were selected at the same ripening level using the DA-Meter. Accordingly, they did not present any color difference among treatments, both for color parameters (a*, b* and L*) and for color indices (h and C). After one week, lighting regimes did not affect colors attributes (Table 1). The absence of color changes at the end of the storage period of ripe red tomatoes grown under supplemental LED light was already observed by the previous research on the effects of pre-harvest LED light on stored tomatoes by Affandi et al. (2021). However, the same research observed a reduction in NAI (Normalized Anthocyanin Index) values as the cold storage period continued, highlighting a possible process of pigment degradation (Farneti et al., 2012). Regarding fruit sweetness and acidity, the absence of differences at harvest time was already observed in previous research (Dzakovich et al., 2015, 2017; Paucek et al., 2020). Several harvest and post-harvest factors affecting fruit metabolic processes can influence the taste and flavor of tomato fruit during storage (Žnidarčič et al., 2010; Beckles, 2012). In our case, the absence of differences in soluble solids and acidity among treatments after one week of storage may be imputed to the advanced ripening stage at harvesting time, having reached the higher amount of storable sugars in fruit while

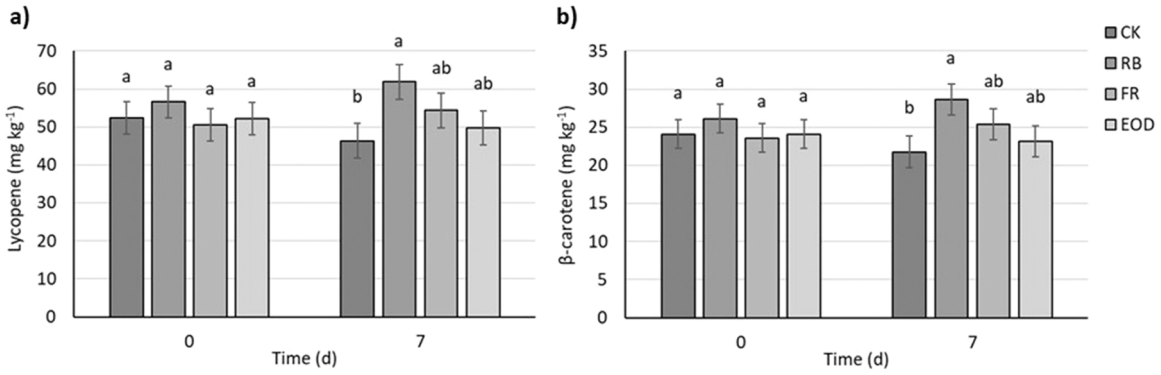

Fig. 2. **a)** Lycopene content (mg kg^{-1}) after 0 and 7 d of storage ($p < 0.05$), ($n = 8$). **b)** β-carotene content (mg kg^{-1}) after 0 and 7 d of storage ($p < 0.05$), ($n = 8$). In charts, vertical bars indicate SD, different letters indicate significant differences at $p < 0.05$.

still attached to the plant (Arias et al., 2000; Carrari et al., 2006), without incurring in soluble solids respiration and consequent reduction during one week of storage (Kader, 1987; Sualeh et al., 2016).

The results of the analysis of antioxidant capacity and total phenols content did not show significant differences between treatments, either at the beginning or at the end of the storage period (Table 1). However, it is well known that light composition affects the expression of genes that modulate the synthesis of secondary metabolites, including phenolic compounds, although such effects may depend on specific wavelength and/or plant species (Gupta, 2017; Baenas et al., 2021; Appolloni et al., 2022). Concerning the antioxidant capacity, several authors have reported an increase in response to the application of LED lighting during the storage of tomatoes, either when a UV or Red and Blue LED light was used (Liu et al., 2011; Baenas et al., 2021). However, several other factors contribute to fruit's antioxidant capacity, including climatic factors and ripeness (Valiulina et al., 2015), which may have masked the light-induced increase in antioxidant capacity. In fact, overripe fruit tends to lose antioxidant capacity compared to unripe (Valiulina et al., 2015), probably masking a possible effect among the different treatments in our case. Palmitessa et al. (2011) reported an increase in antioxidant capacity, specifically for the lipophilic fraction, also in freshly harvested tomatoes grown with supplemental LED light. Notably, lycopene has been described as a potent antioxidant and the most active in the organic phase against free radicals (Cano et al., 2003; Baenas et al., 2021), and its content after the storage is higher in RB-treated samples and lowest in CK ones (Fig. 2**a**). The absence of differences in antioxidant capacity in our analysis could be associated with the hydrophilic extraction adopted in our protocol (Srivastava and Srivastava, 2015). Concerning total phenols content, both studies that directly applied LED light to tomatoes during post-harvest (Kokalj et al., 2016; Baenas et al., 2021) and additional LED light in pre-harvest without post-storage evaluations (Dzakovich et al., 2017), would seem to confirm little effect on these compounds. However, the lack of significant differences among treatments at T0 and T7 in our research (Table 1) might be driven by a too short storage time (Bravo et al., 2012; Liu et al., 2012; Baenas et al., 2021), which could have limited the differences among treatments also in terms of decay. The present research decided to apply a standard commercial storage of one week as practiced by the farm. However, future research might consider more extended storage periods, using time as a factor to statistically confirm observations. Finally, the differential results from existing literature could also be associated with a different response to the lighting treatment associated with genotypic determinants (Mditshwa et al., 2017).

Carotenoid biosynthesis appears to be stimulated by Red and Blue LED light due to modulation of gene expression and light receptors (Mditshwa et al., 2017; Baenas et al., 2021). In particular, phytochrome appears to be the light receptor most involved in lycopene synthesis, being observed that Red light treatment can increase lycopene content in green-mature tomatoes by 2.3-fold (Alba et al., 2000). In our research, it was observed that lycopene content at harvest time did not differ significantly between treatments. This observation seems to contrast with the former hypothesis that associates LED light applied during pre-harvest with increases in the lycopene content in tomatoes (Ngcobo et al., 2020; Dannehl et al., 2021), although our observation may be related to the uniformity of the fruits used for the storage, all at an advanced stage of ripeness. However, after one week of storage, the treatments showed a significant difference in carotenoids (lycopene and β-carotene) content, particularly between CK grown under natural light only and the RB treatment (Fig. 2**a** and Fig. 2**b**). In the case of FR and EOD treatments, no significant differences were observed compared to CK, although the carotenoid content was still higher (Fig. 2**a** and Fig. 2**b**). An increase in red color of tomatoes is usually associated with an increase in carotenoids content (Carrillo-López and Yahia, 2014). In our case, the tomatoes used for the post-harvest measures were selected at an advanced mature-red stage, possibly having achieved the maximum synthesis of carotenoids. For this reason, it is possible to hypothesize that the differences observed at T7 are more attributable to a different decay time of carotenoids instead to the biosynthesis of new molecules. Indeed, it has been observed that lycopene in red tomatoes stored at 13 °C tends to undergo a decay process (Farneti et al., 2012).

5. Conclusions

The research demonstrated that supplementary LED lighting applied during the cultivation of greenhouse tomatoes might allow maintaining hardness and carotenoid content in mature-red tomatoes after a standard commercial storage period at 13 °C for one week. The observed results on increased fruit hardness are of particular interest from the standpoint of post-harvest handling and transportation losses. A greater skin hardness, which may lead to lower transpiration, can have positive effects on the reduction of food waste due to mechanical damages and weight loss during post-harvest. The absence of alteration of organoleptic features, such as color, sweetness, acidity and consistency of the pulp, may represent a positive aspect for consumers, maintaining unchanged the habitual perception of the product and consequent its marketability. Concerning nutritional value, the higher presence of carotenoids after one week in fruit belonging to plants exposed to LED lighting may be a sign of a slower decay of product compounds, with positive consequences on preserving nutritional properties throughout time. The results open to future perspectives concerning supplemental LED light application to reduce food losses and maintain nutritional traits during post-harvest storage. As preliminary research, future developments could focus on analysis considering a longer time factor, including tomatoes harvested in earlier stages of development than red-mature. Research should also develop toward the evaluation of other crops besides tomato, as well as cost-benefit analysis in terms of the

economic value of food savings compared to costs of LED light application. Finally, since the application of LED light may only have an effect in limiting lighting scenarios, the evaluation of the effect conserving the same Daily Light Integral (DLI) - reducing sunlight with shade cloth in LED treatments, for instance - should also be considered.

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CRediT authorship contribution statement

Elisa Appolloni: Methodology, Formal analysis, Investigation, Data curation, Writing – original draft. **Giuseppina Pennisi**: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision. **Ivan Paucek**: Resources, Data curation. **Antonio Cellini**: Resources, Data curation. **Andrea Crepaldi**: Resources. **Francesco Spinelli**: Conceptualization, Visualization, Supervision, Project administration, Funding acquisition. **Giorgio Gianquinto**: Supervision. **X. Gabarell:** Supervision. **Francesco Orsini**: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ACr was employed by company Flytech srl. All other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.postharvbio.2022.112113.

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