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EFFECT OF GROWING PINK TOMATO PLANTS WITH LED SUPPLEMENTARY LIGHTING IN A GREENHOUSE COVERED WITH DIFFUSION GLASS ON POST-HARVEST FRUIT QUALITY

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ABSTRACT

It was found that the taste and quality of tomato fruit can significantly depend on the cultivar, growing conditions, fruit maturity stage, and post-harvest treatments. This study aimed to compare the effects of growing conditions, such as the use of diffusion glass and LED supplementary light (LED+D), with diffusion and standard glass and HPS lamps (HPS+D; HPS) on the quality and post-harvest shelf life of pink tomato fruit cv. 'Tomimaru Muchoo F1' in relation to fruit maturity stage and storage temperature. Fruits were harvested at three ripening stages – mature green (MG), breaker (B) and fully ripe (FR). Fruits of each maturity stage were stored under controlled conditions in a cold store at 12 °C for MG and B fruits and at 6 °C for FR fruits (at 85% relative humidity), and 20 °C for all ripening stages (at about 50% relative humidity). Physiological weight loss, dry weight, hardness of fruit, fruit color (L*, a*, b*, a*/b*), total soluble solids, total sugars, ascorbic acid, titratable acidity, pH, lutein, lycopene, α-carotene, β-carotene were determined. Pink tomato fruits harvested from LED-lighted plants in combination with diffusion glass showed the highest shelf life and post-harvest quality compared to fruits from HPS-lighted plants and HPS-lighted crops in combination with diffusion glass. Stored pink tomato fruits from the LED+D combination were characterized by significantly higher total sugars, vitamin C and β-carotene content than fruits from the combination HPS and HPS+D. Tomato fruits, regardless of the maturity stage, at 20 °C had higher fresh weight loss and lower fruit firmness during storage compared to those stored at lower temperatures. Pink tomato fruits stored in higher temperature colored faster and contained a higher concentration of components such as total soluble solids or ascorbic acid and carotenoids.

Keywords: harvesting stage, storage duration, physiological weight loss, total sugars, ascorbic acid, carotenoids

INTRODUCTION

Growing vegetables under protected conditions makes it possible to obtain a high yield of vegetables of predictable quality. This applies to crops grown throughout the year, regardless of the conditions in a given climatic zone.

Light is a key environmental factor affecting the crop yield's size and quality. Intensive production of crops under protected conditions is limited by insufficient quantity and quality of sunlight throughout the year. Therefore, in modern, year-round greenhouse

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facilities, to optimize light conditions, applications include such solutions as diffusion glass for covering the roof slopes of greenhouses and lamps for assimilation lighting. Light intensity and its quality and distribution in the plant canopy play an important role in the physiological and biochemical processes of the plant, and this is reflected in the volume and quality of the yield [Li et al. 2014a, Guo et al. 2016, Kumar et al. 2016, Zhang et al. 2019].

The results of many studies have proven the beneficial effect of diffused light on the cultivation of both vegetables and ornamental plants [Hemming et al. 2008, Dueck et al. 2012, Li et al. 2014b]. According to Holsteens et al. [2020], in tomato cultivation, the beneficial effect of diffused light (due to the use of diffusion glass) depends on the season, plant density in the facility and plant architecture.

Assimilation lighting with both HPS and LED lamps increases vegetable yield compared to crops that are not lighted. Moreover, the use of supplemental LED inter-row lighting in crops at high plant densities increases the productivity of vegetable crops [Gómez and Mitchell 2016, Appolloni et al. 2021]. The result of such lighted production is also affected by the quality of the light.

Solid-state lighting using light-emitting diodes (LEDs) represents a technology fundamentally different from the gas discharge lamps traditionally used in horticulture. As a result of conducting many studies on the effects of light wavelengths on the growth, yield and nutritional quality of greenhouse vegetables, it can be concluded that red, blue and green light are the main light colors that positively affect the yield, growth and nutritional quality of crops. Other light colors, such as far red, orange light and UVA light, are also beneficial [Olle and Viršile 2013, D'Souza et al. 2015, Olle and Alsina 2019]. Many papers have reported the benefits of supplementary lighting of tomatoes with blue light and far-red light [Kim et al. 2020, Appolloni et al. 2021].

Tomatoes are one of the most widely grown vegetables in the world, and fruits are prized for their flavor and nutritional value. Tomatoes contain soluble sugars and organic acids and are rich in vitamins, flavonoids, carotenoids, polyphenols, amino acids, mineral salts and other bioactive compounds [Garbowicz et al. 2018, Liu et al. 2018]. Eating tomatoes can prevent cancer and other civilization diseases and offer great health benefits [Lenucci et al. 2006].

The pink-fruited tomato is very popular in Central and Eastern European countries. It is valued by consumers primarily for its very good taste and aroma [Kim et al. 2021].

It was found that the taste and quality of tomato fruit can significantly depend on the cultivar, growing conditions, fruit maturity stage, and post-harvest treatments [Li et al. 2019, Zeng et al. 2022]. In addition, the high post-harvest quality of tomato fruit is highly desirable and depends on many factors, from the cultivar to the growing conditions, as well as the method and length of storage [Khairia et al. 2015]. The stage of ripeness at which the tomato fruit is harvested also has a very great influence on its post-harvest quality. According to Al-Gaadi et al. [2024], tomato fruits can be stored at 12 °C temperature for up to 20–24 days without negative effects on fruit quality. However, there are still few reports on the storage of pink tomato fruit.

The aim of the current study was to compare the effects of growing conditions, such as the use of diffusion glass and LED supplementary light, compared to cultivation in a greenhouse with standard glass and HPS lamp on the quality and post-harvest shelf life of pink tomato fruit in relation to fruit maturity stage and storage temperature.

MATERIALS AND METHODS

Location of research. Tomatoes were grown under controlled conditions at the Greenhouse Experimental Center of the Warsaw University of Life Sciences (21°E, 51°15'N) at the Institute of Horticultural Sciences in the Department of Vegetable and Medicinal Plants. The research was conducted in three greenhouse chambers, each with a usable area of about 40 m^2. Chamber 1 (control, HPS), in the roof area, was covered with typical greenhouse glass and equipped with overhead lighting, standard for plant assimilation lighting, and HPS lamps (Gavita GAN 400 W), 24 per chamber. Chamber 2 (HPS+D), in the roof section, was covered with diffusion glass and equipped with upper lighting of HPS lamps (Gavita GAN 400 W), 24 per chamber. Chamber 3 (LED+D), in the roof section, was covered with diffusion glass-like chamber 2 and equipped with top and inter-row LED lamps. Top lighting was provided by Philips Green Power LED lamps (DR/W – LB, 195 W) with 24 units, emitting 220 µmol m^{-2} s^{-1} PPFD (photosynthetic photon flux density) and two lines of inter-row LED lamps, each emitting 50 µmol m^{-2} s^{-1} PPFD Philips Green Power LED (2.5 m HO DR/B 100 W modules) with 18 units per chamber. In each chamber, PAR (photosynthetically active radiation) light conditions were maintained at one level, about ~320 µmol m^{-2} s^{-1} PPFD. The plants were lighted 16 hours a day. The climate computer automatically turned off the LED lamps and HPS overhead lighting at the current solar radiation of 300W/m^2. The inter-row lighting lamps were on for 16 hours per day regardless of the current solar radiation. The CO_2 concentration in the chamber was maintained at 800 ppm.

Plant material. Pink tomatoes, cultivar 'Tomimaru Muchoo F_1' of Dutch breeder De Ruiter Seeds, currently branded by Bayer, were grown in chambers in Rockwool mats (Cutilene, Rijen, Holland). Tomato plant seedlings were planted on 17 September 2020 in each chamber in three rows at a density of 3.15 shoots per m^2 of usable area. For the fertigation of plants with a capillary system, a 100-times concentrated nutrient solution in tanks prepared from single fertilizers of Yara Poland Ltd. was used. The working medium was prepared and dosed using a computer with a fertilizer mixer with automatic control of the pH and EC of the medium. Fruits were harvested twice a week. The study aimed to evaluate the post-harvest quality of pink tomato fruits cultivated under different lighting conditions. This included comparing tomatoes grown in a facility with standard greenhouse glass illuminated by HPS lamps (HPS) to those grown with HPS lighting in a facility featuring diffusion glass (HPS+D). Additionally, tomatoes were grown using LED lighting from above and between the rows, where traditional glass in the facility was also replaced by diffusion glass (LED+D). The data were collected during the full fruiting stage of the plants in the 5th week of the year.

The method of choosing the fruit to be investigated. Fruits were harvested at three ripening stages (mature green – MG; breaker, the color of fruits changes from green to red – B; and fully ripe – FR), at least six fruits from three different plants (three biological replicates) for each combination. Fruits were placed in openwork plastic boxes. Tomato fruits of each maturity stage were stored under controlled conditions in a cold store at two temperatures. The lower temperature was 12 °C for MG and B fruits and 6 °C for FR fruits (at 85% relative humidity), while the higher temperature was 20 °C room temperature for all ripening stages (at about 50% relative humidity). MG and B fruits were tested after 1, 2 and 3 weeks of storage and FR after 1 and 2 weeks of storage. Analyses of the physical and chemical parameters of the fruit were performed in each combination of three replicates

Analysis of physical parameters. Physiological weight losses were calculated by weighing fruit from each combination and repetition, recording the initial weight. For three consecutive weeks of storage, fruits were weighed on a laboratory scale to two decimal places. Percentage weight loss was calculated as follows [Rab et al. 2013] and parameter physiological weight loss (PWL) was expressed in %.

$$\text{Percent weight loss} = \frac{\text{Weight of fresh fruit} - \text{Weight after storage}}{\text{Weight of fresh fruit}} \times 100\%$$

Plant dry matter content was determined by drying fruit samples in an oven at 105 °C for 24 h. Dry weight (DW) was expressed in %.

Hardness was measured on three randomly selected fruits using the HPE hardness tester with a 5 mm shank diameter at a 90° angle to the fruit, averaging the result from three measurements: at the stem end, at the center of the fruit, and at the blossom end. The results were given on the HPE scale from 0–100 units. The hardness of fruit (H) was also expressed on the HPE scale.

Fruit color was measured using a MiniScan XE PLUS D/8-S portable reflected light color spectrophotometer on the CIE Lab scale. For the red color share (a*), positive values of the coordinate refer to red color share, negative values refer to green color share. For the yellow color share (b*), positive values of the coordinate refer to yellow color share and negative values refer to blue color share. The coloration index (a*/b* ratio) and L* brightness were determined on a scale from 0 (black) to 100 (white) [López Camelo and Gomez 2004].

Analysis of chemical parameters

Total soluble solids (TSS) were determined by refractometric method using a digital refractometer (Hanna Instruments HI-96800), giving the result in °Brix.

Total sugar content (TS) measured with the Luff-Schoorl method [Gormley and Maher 1990] was expressed in %.

Ascorbic acid content (AA) was measured using Tillman's method [Aćamović-Djoković et al. 2011] and expressed in mg 100 g^{-1}.

Titratable acidity (TA) was obtained by titrating 5 mL of tomato juice with 0.1 N NaOH up to pH 8.1. TA was expressed in %.

Potentiometric acidity (pH) using the method involves measuring the electromotive force of a cell consisting of a glass electrode (indicator electrode) and a reference electrode (reference electrode) immersed in a test solution (pH meter by HANNA Instruments model HI2211).

Lutein, lycopene, α-carotene and β-carotene content were measured by the HPLC method. Samples (1 g FW) were ground with Na_2CO_3 (50 : 1 w/w ratio, Merck Darmstadt, Germany), quartz sand and 15 mL of cold acetone (–4 °C) in limited lighting conditions. The extracts were filtered into 50 mL volumetric flasks, filled with cold acetone and centrifuged for 10 minutes at 15,000 rpm at 4 °C (Centrifuge 5430R, Eppendorf, Hamburg, Germany). The supernatant was also filtered through a hydrophobic PTFE 25 mm × 0.22 µm syringe filter (Supelco IsoDisc, Supelco Analytical, Bellefonte, USA). The separation was executed on Shimadzu Prominence HPLC, equipped with two pumps LC-20AD, auto-sampler SIL-20AC HT, column oven CTO-10AS VP, diode-array UV/VIS detector SPD-M20A and LC solution 1.21 SP1 chromatography software (Shimadzu, Kyoto, Japan), using ODS 2.6 µm solid-core, 100 × 4.60 mm column (Kinetex™, Phenomenex®, Torrance, USA) and methanol (for HPLC ≥99.9% Merck, Darmstadt, Germany) as a mobile phase with isocratic elution at a flow rate of 1.4 mL · min^{-1} (Tab. 1). The injection volume was 5 µL. The column temperature was set at 30 °C. The detection UV wavelength was set at 430 nm for chlorophyll a, 445 nm for lutein and α-carotene, 450 nm for β-carotene, and 470 nm for chlorophyll b. Compounds were identified by retention time as well as UV-spectra (190–450 nm) comparison with standards. The content of the determined compounds was expressed in mg·100 g^{-1} fresh weight.

Statistical analysis. The data were subjected to analysis of variance (ANOVA) using Statistica 13.3 software. The differences between means of combinations were evaluated by post hoc Tukey's honestly significant difference (HSD) test. The means were considered to be significantly different at $p < 0.05$.

RESULTS

Physical properties of fruit: physiological weight loss (PWL), dry weight (DW), hardness and color

After one week of storage of 'Tomimaru Muchoo F_1' pink tomato fruits, whether harvested at the fully ripe, mature green or breaker fruit stages, there were no significant differences in the amount of physiological weight loss depending on growing conditions (HPS, HPS+D, LED+D) or post-harvest storage temperature (Tab. 2–5). For mature green fruit, weight loss (PWL) after one week of storage ranged from 2.60% to a maximum of 3.26% (Tab. 2), and for breaker fruit, from 1.7% to 2.37% (Tab. 3).

Table 1. HPLC-DAD validation parameters (n = 6)

Compound	t_R	Precision intra-day (CV%)	Precision inter-day (CV%)	Calibration equation	R^2 (n = 6)	Linear range (µg · mL^{-1})	LOD (µg · L^{-1})	LOQ (µg · L^{-1})
Lutein	0.75	0.51	0.95	y = 10319.0 x + 159.5	0.999	0.51–10.15	0.54	1.79
Chlorophyll b	1.27	0.48	0.79	y = 5109.2 x + 499.8	0.999	1.40–28.00	0.13	0.43
Chlorophyll a	1.80	0.53	0.98	y = 3222.4 x + 128.6	0.999	1.31–26.11	0.98	3.29
α-carotene	3.30	0.40	0.69	y = 8077.9 x – 43.7	0.999	30.81–3081.00	0.86	2.88
β-carotene	3.75	0.23	0.54	y = 4394.0 x – 111.0	0.999	44.70–4470.00	1.04	3.49

Table 2. Influence of growing conditions on selected quality parameters of the mature green (MG) fruits of pink tomato cultivar 'Tomimaru Muchoo' stored at 12 °C and 20 °C for one, two and three weeks

Parameter	Unit	Storage period (week)	12 °C			20 °C		
			HPS	HPS+D	LED+D	HPS	HPS+D	LED+D
Physiological weight loss (PWL)	%	1	2.37 ns*	2.08 ns	1.70 ns	1.93 b*	2.30 a	2.10 ab
		2	3.54 ab	4.16 a	2.62 b	4.19 ns	4.46 ns	4.27 ns
		3	6.15 ns	5.22 ns	5.93 ns	6.68 ns	6.92 ns	6.30 ns
Dry weight (DW)	%	1	4.17 b	4.80 ab	5.24 a	4.82 ns	5.09 ns	4.72 ns
		2	5.50 ns	5.00 ns	5.62 ns	5.70 ab	4.93 b	5.93 a
		3	5.40 ns	5.57 ns	5.46 ns	4.95 ns	5.40 ns	5.33 ns
Hardness (H)	HPE scale	1	41.83 b	49.12 a	47.05 a	36.43 ab	34.32 b	39.73 a
		2	35.18 ns	36.55 ns	36.47 ns	30.02 ab	32.65 a	27.13 b
		3	30.58 a	31.42 a	27.67 b	22.93 ns	22.40 ns	21.00 ns
L*		1	46.29 ns	46.47 ns	43.43 ns	41.92 ns	41.41 ns	42.57 ns
		2	43.00 ns	41.73 ns	42.52 ns	40.28 ns	39.10 ns	38.76 ns
		3	41.91 a	41.83 a	40.00 b	41.13 ns	39.59 ns	39.34 ns
a*		1	19.03 ns	18.95 ns	19.86 ns	24.00 ns	23.78 ns	22.24 ns
		2	22.39 ns	21.55 ns	21.90 ns	24.59 ns	24.58 ns	24.36 ns
		3	22.67 ns	22.59 ns	22.27 ns	23.73 ns	23.67 ns	22.56 ns
b*		1	16.34 ns	16.35 ns	16.69 ns	16.07 ns	16.17 ns	15.81 ns
		2	17.86 ns	17.57 ns	17.54 ns	18.41 ns	17.82 ns	17.50 ns
		3	18.19 ns	18.51 ns	17.35 ns	19.29 ns	19.28 ns	18.23 ns
a*/b*		1	1.16 ns	1.16 ns	1.19 ns	1.49 ns	1.47 ns	1.41 ns
		2	1.25 ns	1.23 ns	1.25 ns	1.34 ns	1.37 ns	1.40 ns
		3	1.25 ns	1.22 ns	1.28 ns	1.23 ns	1.24 ns	1.24 ns
Total soluble solids (TSS)	°Brix	1	4.33 b	4.40 b	4.77 a	4.47 b	4.73 a	4.43 b
		2	4.47 b	4.23 c	4.60 a	4.33 b	4.10 c	4.63 a
		3	4.50 ns	4.57 ns	4.53 ns	4.30 ns	4.40 ns	4.50 ns
Total sugars (TS)	%	1	1.87 ns	1.86 ns	2.19 ns	1.79 b	2.22 a	2.19 a
		2	2.12 b	2.02 b	2.54 a	2.14 b	1.99 b	2.52 a
		3	1.81 ns	1.79 b	1.89 ns	1.79 ab	1.69 b	1.92 a
Ascorbic acid (AA)	mg·100 g^{-1} FW	1	16.76 b	16.39 b	20.71 a	21.09 ns	19.82 ns	20.00 ns
		2	20.27 b	16.76 c	23.77 a	23.84 b	19.97 c	30.70 a
		3	21.16 b	20.86 b	26.82 a	28.31 c	30.16 b	32.93 a
Titratable acidity (TA)	%	1	0.70 b	0.75 a	0.64 c	0.65 ns	0.61 ns	0.59 ns
		2	0.57 a	0.53 ab	0.52 b	0.47 ab	0.50 a	0.45 b
		3	0.49 na	0.53 ns	0.49 ns	0.42 ab	0.44 a	0.41 b
pH		1	4.31 ns	4.32 ns	4.36 ns	4.39 ns	4.40 ns	4.39 ns
		2	4.44 b	4.50 a	4.40 c	4.54 ns	4.50 ns	4.53 ns
		3	4.48 ns	4.48 ns	4.44 ns	4.55 ns	4.59 ns	4.55 ns
Lutein	mg·100 g^{-1} FW	1	0.039 ab	0.035 b	0.048 a	0.043 a	0.031 b	0.046 a
		2	0.047 a	0.032 b	0.036 b	0.039 ns	0.045 ns	0.040 ns
		3	0.028 b	0.028 b	0.038 a	0.030 b	0.0268 ns	0.046 ns
Lycopene	mg·100 g^{-1} FW	1	5.35 ns	6.36 ns	5.27 ns	4.54 ab	4.76 a	3.93 b
		2	8.33 a	2.66 c	6.30 b	7.14 ns	6.61 ns	7.15 ns
		3	2.35 c	5.76 a	4.03 b	4.10 ns	3.48 ns	5.99 ns
α-carotene	mg·100 g^{-1} FW	1	0.057 ns	0.073 ns	0.064 ns	0.048 a	0.035 b	0.036 b
		2	0.071 a	40 c	0.055 b	0.027 c	0.038 b	0.045 a
		3	0.041 ns	0.022 ns	0.048 ns	0.022 ns	0.022 ns	0.032 ns
β-carotene	mg·100 g^{-1} FW	1	1.03 ns	1.15 ns	1.10 ns	0.80 b	0.55 c	0.97 a
		2	1.22 a	0.75 c	0.95 b	0.64 b	0.64 b	0.82 a
		3	0.99 a	0.77 b	1.02 a	0.41 ns	0.34 ns	0.77 ns

*Average values in the same row marked with ns or marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$

Fruits harvested at the fully ripe stage, already after one week of storage, had a higher weight loss when stored at 20 °C compared to 6 °C. Weight losses for these fruits after one week of storage were 1.23% for 20 °C, compared to 0.55% for 6 °C. After two weeks of storage, the losses increased to 3.48% and 1.23%, respectively (Tab. 4).

Fruits harvested at the mature green stage from plants lighted by sodium lamps, which grew in a greenhouse where the roof was covered with diffusion glass and which were stored at 20 °C, had the highest weight losses after two weeks and three weeks of storage, compared to other combinations (Tab. 2).

The dry weight of tomato fruit increased during storage, especially for fruit harvested at the fully ripe stage and stored for more than a week (Tab. 4). A similar trend was found for longer-stored fruit harvested at the breaker fruit stage (Tab. 3).

Fruit hardness, regardless of the maturity stage of the fruit, was already significantly lower after one week of storage for fruit stored at higher temperatures and decreased with the length of the storage (Tab. 2–4).

The color characteristics of tomato fruit in the CIE Lab scale for the L* parameter (lightness) for the mature green fruit did not change significantly during storage, regardless of the combination. On the other hand, a significantly lower value of L* was found during subsequent weeks of storage for mature green fruit (Tab. 2). The greatest changes in the value of the L* parameter for breaker fruit were found between the first and second week of storage in the combinations of HPS at 12 °C, HPS+D at 12 °C, and LED+D at 20 °C (Tab. 3). On the other hand, fully ripe fruit stored for one and two weeks showed no significant difference in skin lightness determined by the L* parameter (Tab. 4). The red color parameter a* for mature green fruit stored for one week took negative values in the combination of HPS at 12 °C and LED+D at 12 °C. In subsequent weeks of storage, the intensity of the red color was similar in all combinations (Tab. 2). Already after one week of storage of the breaker fruit at a higher temperature (20 °C), regardless of the combination, the red color parameter a* was higher than for fruit stored at 12 °C. In the subsequent second and third weeks of storage of breaker fruit, the red color parameter for skin color was similar for all combinations, regardless of storage temperature (Tab. 3). For fully ripe fruit, the a* parameter was also similar for all combinations, regardless of temperature and storage time, and ranged from 22.96 to 25.39 (Tab. 4). In the stored breaker fruit, after three weeks of storage in combinations of HPS at 20 °C and HPS+D at 12 °C and 20 °C, there was a significant increase in yellow color (parameter b*) compared to breaker fruit from these combinations and stored for one week (Tab. 3). The color index a*/b* increased the most for mature green fruit stored for more than a week (Tab. 2). In contrast, a*/b* index values were found to decrease for fully ripe fruit stored for two weeks in the combination of HPS at 6 °C.

Analysis of chemical parameters

Total soluble solids (TSS), total sugars (TS), ascorbic acid (AA), titratable acidity (TA), pH. After one week of storage, mature green fruit from the combination of HPS+D at 12 °C and LED +D at 20 °C showed a higher proportion of soluble components in cell juice (TSS) than other fruit. Such differences were not found for the fruit TS content. However, after two weeks of mature green fruit storage, an increase in the accumulation of TSS and TS was found for the fruit from the combinations of HPS at 20 °C, HPS+D at 20 °C, and LED+D at 12 °C, and in the following week (3rd) of storage, a decrease in TSS was noted in fruit stored at a higher temperature (20 °C) compared to fruit stored for two weeks at this temperature. In contrast, there was no significant decrease in TS in these fruits after three weeks of storage (Tab. 2).

The highest TSS content after one week of storage of breaker fruit was found for the fruit from the combinations of HPS+D at 20 ˚C and LED+D at 12 °C. On the other hand, breaker fruit from the combination of HPS stored at 20 °C showed the lowest content of TS (Tab. 3).

Fruits harvested at fully ripe stage, after one week of storage, showed the highest TSS in the combination of LED+D at 20 °C, and after two weeks of storage, the amount of TSS in the fruit from the combination of HPS at 6 ˚C and LED+D at 6 °C increased. At the same time, the total sugar content increased in these fruits. There were also high TSS and TS contents in fully ripe fruit from LED+D conditions and a storage temperature of 20 °C (Tab. 4). Mature green fruit from the

Table 3. Influence of growing conditions on selected quality parameters of the breaker (B) fruits of pink tomato cultivar 'Tomimaru Muchoo' stored at 12 °C and 20 °C for one, two and three weeks

Parameter	Unit	Storage period (week)	12 °C			20 °C		
			HPS	HPS+D	LED+D	HPS	HPS+D	LED+D
Physiological weight loss (PWL)	%	1	2.37 ns*	2.08 ns	1.70 ns	1.93 b	2.30 a	2.10 ab
		2	3.54 ab	4.16 a	2.62 b	4.19 ns	4.46 ns	4.27 ns
		3	6.15 ns	5.22 ns	5.93 ns	6.68 ns	6.92 ns	6.30 ns
Dry weight (DW)	%	1	4.17 b	4.80 ab	5.24 a	4.82 ns	5.09 ns	4.72 ns
		2	5.50 ns	5.00 ns	5.62 ns	5.70 ab	4.93 b	5.93 a
		3	5.40 ns	5.57 ns	5.46 ns	4.95 ns	5.40 ns	5.33 ns
Hardness (H)	HPE scale	1	41.83 b	49.12 a	47.05 a	36.43 ab	34.32 b	39.73 a
		2	35.18 ns	36.55 ns	36.47 ns	30.02 ab	32.65 a	27.13 b
		3	30.58 a	31.42 a	27.67 b	22.93 ns	22.40 ns	21.00 ns
L*		1	46.29 ns	46.47 ns	43.43 ns	41.92 ns	41.41 ns	42.57 ns
		2	43.00 ns	41.73 ns	42.52 ns	40.28 ns	39.10 ns	38.76 ns
		3	41.91 a	41.83 a	40.00 b	41.13 ns	39.59 ns	39.34 ns
a*		1	19.03 ns	18.95 ns	19.86 ns	24.00 ns	23.78 ns	22.24 ns
		2	22.39 ns	21.55 ns	21.90 ns	24.59 ns	24.58 ns	24.36 ns
		3	22.67 ns	22.59 ns	22.27 ns	23.73 ns	23.67 ns	22.56 ns
b*		1	16.34 ns	16.35 ns	16.69 ns	16.07 ns	16.17 ns	15.81 ns
		2	17.86 ns	17.57 ns	17.54 ns	18.41 ns	17.82 ns	17.50 ns
		3	18.19 ns	18.51 ns	17.35 ns	19.29 ns	19.28 ns	18.23 ns
a*/b*		1	1.16 ns	1.16 ns	1.19 ns	1.49 ns	1.47 ns	1.41 ns
		2	1.25 ns	1.23 ns	1.25 ns	1.34 ns	1.37 ns	1.40 ns
		3	1.25 ns	1.22 ns	1.28 ns	1.23 ns	1.24 ns	1.24 ns
Total soluble solids (TSS)	°Brix	1	4.33 b	4.40 b	4.77 a	4.47 b	4.73 a	4.43 b
		2	4.47 b	4.23 c	4.60 a	4.33 b	4.10 c	4.63 a
		3	4.50 ns	4.57 ns	4.53 ns	4.30 ns	4.40 ns	4.50 ns
Total sugars (TS)	%	1	1.87 ns	1.86 ns	2.19 ns	1.79 b	2.22 a	2.19 a
		2	2.12 b	2.02 b	2.54 a	2.14 b	1.99 b	2.52 a
		3	1.81 ns	1.79 b	1.89 ns	1.79 ab	1.69 b	1.92 a
Ascorbic acid (AA)	mg·100 g^{-1} FW	1	16.76 b	16.39 ef	20.71 a	21.09 ns	19.82 ns	20.00 ns
		2	20.27 b	16.76 c	23.77 a	23.84 b	19.97 c	30.70 a
		3	21.16 b	20.86 b	26.82 a	28.31 c	30.16 b	32.93 a
Titratable acidity (TA)	%	1	0.70 b	0.75 a	0.64 c	0.65 ns	0.61 ns	0.59 ns
		2	0.57 a	0.53 ab	0.52 b	0.47 ab	0.50 a	0.45 b
		3	0.49 na	0.53 ns	0.49 ns	0.42 ab	0.44 a	0.41 b
pH		1	4.31 ns	4.32 ns	4.36 ns	4.39 ns	4.40 ns	4.39 ns
		2	4.44 b	4.50 a	4.40 c	4.54 ns	4.50 ns	4.53 ns
		3	4.48 ns	4.48 ns	4.44 ns	4.55 ns	4.59 ns	4.55 ns
Lutein	mg·100 g^{-1} FW	1	0.039 ab	0.035 b	0.048 a	0.043 a	0.031 b	0.046 a
		2	0.047 a	0.032 b	0.036 b	0.039 ns	0.045 ns	0.040 ns
		3	0.028 b	0.028 b	0.038 a	0.030 b	0.0268 ns	0.046 ns
Lycopene	mg·100 g^{-1} FW	1	5.35 ns	6.36 ns	5.27 ns	4.54 ab	4.76 a	3.93 b
		2	8.33 a	2.66 c	6.30 b	7.14 ns	6.61 ns	7.15 ns
		3	2.35 c	5.76 a	4.03 b	4.10 ns	3.48 ns	5.99 ns
α-carotene	mg·100 g^{-1} FW	1	0.057 ns	0.073 ns	0.064 ns	0.048 a	0.035 b	0.036 b
		2	0.071 a	40 c	0.055 b	0.027 c	0.038 b	0.045 a
		3	0.041 ns	0.022 ns	0.048 ns	0.022 ns	0.022 ns	0.032 ns
β-carotene	mg·100 g^{-1} FW	1	1.03 ns	1.15 ns	1.10 ns	0.80 b	0.55 c	0.97 a
		2	1.22 a	0.75 c	0.95 b	0.64 b	0.64 b	0.82 a
		3	0.99 a	0.77 b	1.02 a	0.41 ns	0.34 ns	0.77 ns

* See Table 2

HPS and HPS+D combinations stored for one week at 12 °C had lower ascorbic acid content than fruit from the other combinations (Tab. 2), and the same was true for breaker fruit stored for one week (Tab. 3). Fully ripe fruit from the combinations HPS+D and LED+D after one week of storage at 20 °C had the highest ascorbic acid content. In the following weeks of storage, the AA content for mature green fruit increased and was higher for the fruit from the combination with a storage temperature of 20 °C than 12 °C, regardless of the light conditions in which the fruit grew (Tab. 2). Similarly, the AA content of stored breaker fruit and fully ripe fruit increased (Tab. 3 and 4). Fully ripe fruit, after two weeks of storage, had the highest AA content, especially those stored at higher temperatures, from the HPS and LED+D combinations.

After one week of mature green fruit storage, lower TA and higher pH of cell juice were characteristic of the fruit from plants grown in LED+D and HPS+D light conditions and stored at 20 °C. With each successive week of mature green fruit storage, the higher the temperature at which the fruit was stored, regardless of the growing conditions, the acidity of the cell juice decreased, and the pH increased (Tab. 2). Similar relationships were found for stored breaker fruit, although between the fruit stored for two weeks and the fruit stored for three weeks, significant differences in acidity reduction were found only for the combinations of HPS at 12 °C and HPS+D at 20 °C, and a significant increase in pH for the fruit after three weeks of storage compared to the fruit stored for two weeks was noted only in the combination of HPS+D at 20 °C (Tab. 3).

For the fully ripe fruit stored for one week, the highest acidity was found in the case of the combination of HPS+D at 6 °C , and the highest cell juice pH was found in the fruit from the combination of LED+D at 20 °C. In the next week of storage of fully ripe fruit, the total acidity of the cell juice more than doubled. In the fruit from all combinations, the pH of cell juice also increased (Tab. 4).

Carotenoids content

Lutein. The lutein content in the stored mature green fruit decreased during the following weeks of storage. After two weeks of storage, fruit from the LED+D + 12 °C combination contained the most lutein. After three weeks of storage, the concentration of lutein in mature green fruit was the lowest, and there were no differences between fruit from different growing conditions and storage temperatures (Tab. 2). In stored lighted fruit, the decrease in lutein concentration from week to week was not significant (Tab. 3). In contrast, fruit harvested and stored at the fully ripe fruit stage, after one week of storage at the HPS+D and 12 °C combination, had higher lutein concentrations than fruit from other combinations, and the lowest concentrations were in the fruit ripened under HPS+D conditions, but stored for one week at 20 °C. In contrast, two weeks after the start of storage of fully ripe fruit, lutein concentrations were lower in all combinations than in fully ripe fruit after one week of storage (Tab. 4).

Lycopene. Mature green fruit from plants grown under HPS+D and LED+D supplementary lighted conditions and stored at a higher temperature had the highest lycopene concentration after one week. Green fruit from the control, or from HPS conditions, after one and two weeks of storage at 20 °C had higher lycopene concentrations than fruit stored at 12 °C (Tab. 2). Breaker fruit after one week of storage had similar lycopene content, regardless of the conditions under which they ripened and were stored. On the other hand, after another week of storage, the lycopene concentration in fruit from the combination of HPS+D + 12 °C decreased significantly, and after three weeks, the lycopene content in fruit from the combinations of HPS + 12 °C and HPS+D + 20 °C decreased, compared to the lycopene content in fruit stored under these conditions for two weeks (Tab. 3). Fruit ripened after one week of storage had similar lycopene concentrations, regardless of the conditions under which they ripened, except for fruit from the LED+D combination stored for one week at 6 °C, where the lowest lycopene concentrations were found. Similar levels of lycopene were found in fruit from the combinations of HPS+D + 6 °C and HPS + 6 °C stored for two weeks (Tab. 4). In stored fully ripe pink tomato fruit, lycopene concentrations decreased over the next week of storage in all combinations except LED+D + 6 °C, where an increase in lycopene was noted (Tab. 4).

α-carotene and β-carotene. Mature green fruit stored for one week at the higher temperature had higher α-carotene content than mature green fruit also stored for one week but at the lower tempera-

Table 4. Influence of growing conditions on selected quality parameters of the fully ripe (FR) fruits of pink tomato cultivar 'Tomimaru Muchoo' stored at 12 °C and 20 °C for one, two and three weeks

Parameter	Unit	Storage period (week)	12 °C			20 °C		
			HPS	HPS+D	LED+D	HPS	HPS+D	LED+D
Physiological weight loss (PWL)	%	1	0.43 ns*	0.77 ns	0.45 ns	1.22 ns	1.32 ns	1.16 ns
		2	1.08 ns	1.23 ns	1.39 ns	3.47 ns	3.62 ns	3.35 ns
		3	–	–	–	–	–	–
Dry weight (DW)	%	1	3.72 b	4.57 a	4.51 a	4.57 ab	3.81 b	5.12 a
		2	5.58 ns	5.24 ns	5.68 ns	5.04 ns	5.02 ns	5.30 ns
		3	–	–	–	–	–	–
Hardness (H)	HPE scale	1	37.00 ns	34.85 ns	37.90 ns	29.90 b	32.62 a	33.85 a
		2	34.48 b	38.72 a	38.18 a	28.93 a	26.73 a	19.90 b
		3	–	–	–	–	–	–
L*		1	42.96 ns	42.06 ns	40.06 ns	37.09 ns	39.17 ns	36.99 ns
		2	41.71 ns	42.60 ns	40.37 ns	39.65 a	37.61 b	38.47 ab
		3	–	–	–	–	–	–
a*		1	25.11 ns	24.54 ns	24.29 ns	24.20 ns	25.17 ns	24.12 ns
		2	23.54 ns	24.86 ns	22.96 ns	25.37 ns	24.56 ns	25.39 ns
		3	–	–	–	–	–	–
b*		1	18.03 ns	16.91 ns	16.59 ns	15.74 ns	15.77 ns	15.27 ns
		2	21.74 ns	19.02 ns	18.66 ns	18.38 ns	17.22 ns	17.86 nsc
		3	–	–	–	–	–	–
a*/b*		1	1.40 ns	1.45 ns	1.47 ns	1.54 ns	1.61 ns	1.58 ns
		2	1.11 ns	1.32 ns	1.24 ns	1.38 ns	1.43 ns	1.42 ns
		3	–	–	–	–	–	–
Total soluble solids (TSS)	°Brix	1	4.70 ns	4.57 ns	4.53 ns	4.63 ns	4.70 ns	4.97 ns
		2	5.07 a	4.80 b	4.83 b	4.30 c	4.53 b	4.87 a
		3	–	–	–	–	–	–
Total sugars (TS)	%	1	2.16 ns	2.21 ns	2.02 ns	1.51 b	1.84 a	1.97 a
		2	2.59 a	2.14 b	2.51 a	1.81 b	1.59 b	2.32 a
		3	–	–	–	–	–	–
Ascorbic acid (AA)	mg·100g^{-1} FW	1	20.86 ns	19.82 ns	21.01 ns	19.89 c	25.33 b	26.75 a
		2	35.09 a	29.36 b	35.39 a	31.44 b	29.13 c	41.80 a
		3	–	–	–	–	–	–
Titratable acidity (TA)	%	1	0.51 b	0.62 a	0.55 b	0.56 a	0.51 b	0.51 b
		2	1.07 b	1.21 a	1.06 b	1.16 b	1.24 a	1.06 c
		3	–	–	–	–	–	–
pH		1	4.50 a	4.43 b	4.45 b	4.43 c	4.53 b	4.55 a
		2	4.57 a	4.53 b	4.50 b	4.50 b	4.50 b	4.52 a
		3	–	–	–	–	–	–
Lutein	mg·100g^{-1} FW	1	0.087 b	0.103 a	0.083 b	0.078 b	0.053 c	0.081 a
		2	0.041 b	0.042 b	0.050 a	0.043 ns	0.047 ns	0.047 ns
		3	–	–	–	–	–	–
Lycopene	mg·100g^{-1} FW	1	8.60 a	7.53 a	2.59 b	9.02 ns	7.98 ns	9.06 ns
		2	3.45 b	2.91 b	6.65 a	5.92 ns	5.45 ns	6.01 ns
		3	–	–	–	–	–	–
α-carotene	mg·100g^{-1} FW	1	0.065 ns	0.050 ns	0.056 ns	0.058 b	0.048 b	0.073 a
		2	0.041 ns	0.035 ns	0.044 ns	0.044 ns	0.041 ns	0.046 ns
		3	–	–	–	–	–	–
β-carotene	mg·100g^{-1} FW	1	1.097 ns	1.059 ns	1.085 ns	0.970 b	0.890 b	1.171 a
		2	0.790 b	0.700 be	1.000 a	0.690 b	0.700 ab	0.831 a
		3	–	–	–	–	–	–

* See Table 2

Table 5. Influence of growing conditions on selected quality parameters of pink tomato cultivar 'Tomimaru Muchoo' fruits on post-harvest quality regardless of the stage of ripeness of the fruit, the temperature and the duration of storage (average for all ripeness phases of fruit MG, B, and FR and for all temperatures and duration of storage assessed)
.

Parameter	Unit	Growing condition		
		HPS	HPS+D	LED+D
		3.83 ns*	4.44 ns	3.73 ns
Dry weight (DW)	%	5.08 ns	5.09 ns	5.32 ns
Hardness (H)	HPE scale	33.38 ns	35.38 ns	34.75 ns
L*	–	42.44 ns	42.86 ns	41.71 ns
a*	–	21.03 ns	19.7 ns	19.71 ns
b*	–	18.12 ns	18.05 ns	17.44 ns
a*/b*	–	1.19 ns	1.15 ns	1.12 ns
Total soluble solids (TSS)	°Brix	4.44 b	4.46 ab	4.56 a
Total sugars (TS)	%	1.92 b	1.90 b	2.08 a
Ascorbic acid (AA)	mg·100 g^{-1} FW	21.2 b	20.53 b	24.02 a
Titratable acidity (TA)	%	0.65 ns	0.67 ns	0.61 ns
pH	–	4.45 ns	4.46 ns	4.44 ns
Lutein	mg·100 g^{-1} FW	0.045ns	0.044 ns	0.049 ns
Lycopene		4.94 ns	4.56 ns	4.81 ns
α-carotene		0.046 ns	0.043 ns	0.047 ns
β-carotene		0.79 b	0.71 b	0.86 a

*Average values in the same row marked with ns or marked with the same letters are not significantly different within the analyzed parameter at $p < 0.05$

ture variants used, regardless of growing conditions, while the highest α-carotene concentration was found in fruit from the HPS+D + 20 °C combination. The concentration of α-carotene decreased in the subsequent weeks of mature green fruit storage (Tab. 2). In contrast, breaker fruits stored for one week contained more α-carotene when stored at a lower temperature (12 °C) than at 20 °C, especially from the HPS+D and LED+D combinations. After three weeks of storage, the concentration of α-carotene decreased and was the lowest when the fruits were stored at a higher temperature (Tab. 3). Fully ripe fruit from the LED+D combination stored for one week at 20 °C featured the highest α-carotene content. After another week of storage, α-carotene content decreased in all fruits but was significantly lower in fruit from the LED+D at 20 °C and HPS at 6 °C combinations, compared to fruit after one week of storage (Tab. 4).

Mature green fruit stored for one week contained a higher β-carotene content in the combination of HPS+D at 20 °C. In subsequent weeks of storage of tomato fruit, the concentration of β-carotene in tomato fruit decreased and reached the lowest concentration in mature green fruit stored for three weeks in the combinations of HPS at 20 °C and LED+D at 12 °C (Tab. 2). Breaker fruit after one week of storage at 20 °C had less β-carotene in the combinations of HPS and HPS+D than fruits in other combinations. The lowest β-carotene concentration was found in fruits harvested at maturity stage breaker from plants grown with HPS lighting and stored at 20 °C after three weeks (Tab. 3).

Fully ripe fruit stored for one week at 6 °C had similar β-carotene levels of 1.059 to 1.097 mg/100 g FW in most combinations, and that stored at 20 °C had the highest content of β-carotene in the LED+D combination (1.171 mg/100 g FW). After another week of storage, the concentration of β-carotene in fully ripe fruit decreased. On the other hand, the highest β-carotene concentration after two weeks of storage of the fully ripe fruit was found for the combination of LED+D at 6 °C (Tab. 4).

When comparing the average results for the various factors analyzed (Fig. 1–3), it was found that the

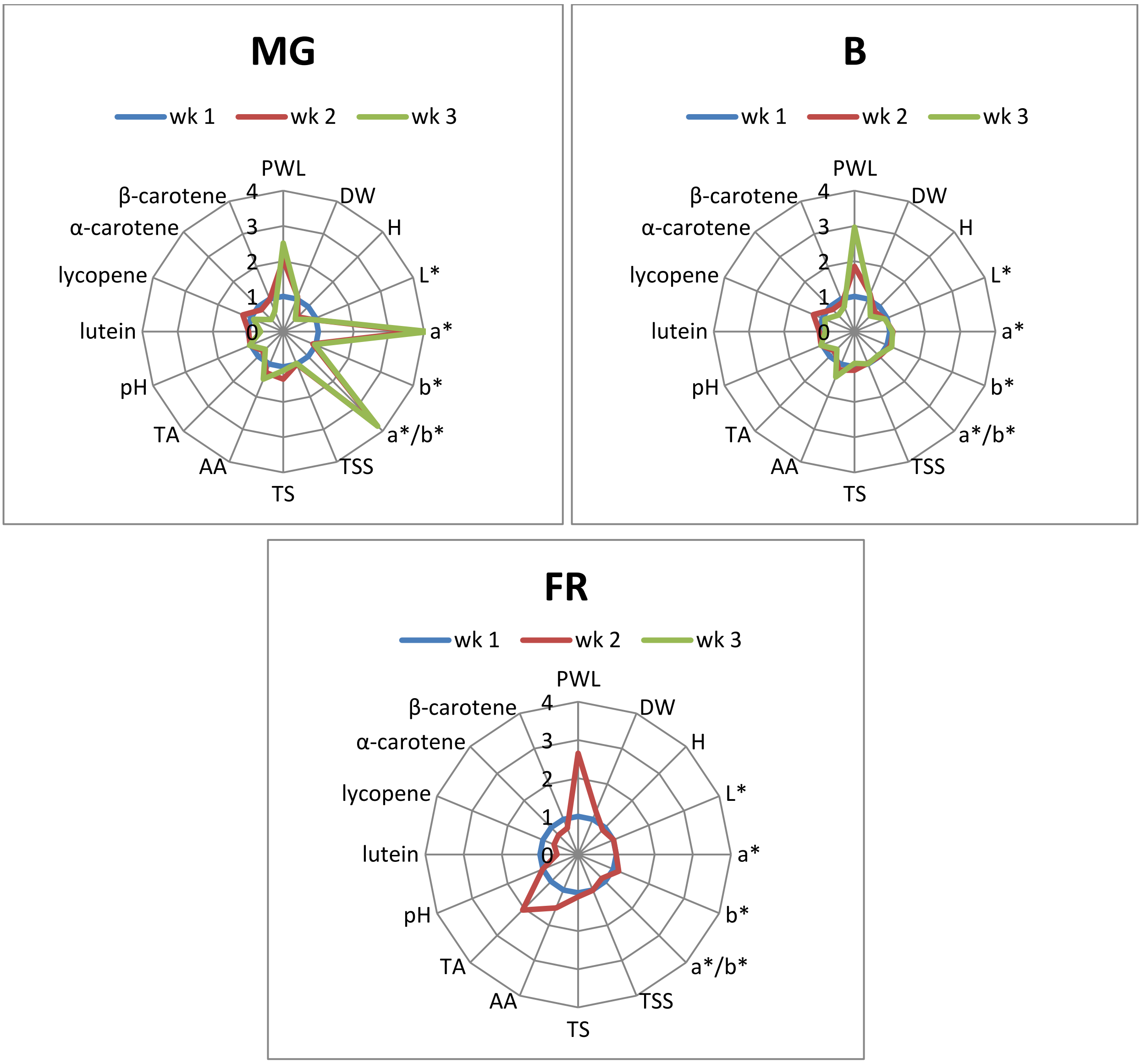

Fig. 1. Influence of storage time (week) on selected quality parameters of the fruits with different degrees of maturity: mature green (MG), breaker (B) and fully ripe (FR) of pink tomato cultivar 'Tomimaru Muchoo'

loss of fresh weight of the tomato fruit increased in subsequent weeks of storage, regardless of the initial stage of maturity of the stored fruit. During storage, the dry weight content of pink tomato fruits increased while their firmness significantly decreased. It was found in stored mature green and breaker fruits that the L* of the skin decreased during storage, and the proportion of red (a*) and yellow (b*) color increased in breaker and fully ripe fruits. For mature green fruit, the coloration index (a*/b* ratio) increased in successive weeks, while for breaker and fully ripe fruit, this index decreased with longer storage. In the longer-stored mature green and breaker fruit, the TSS content decreased significantly, and the content of TS increased after two weeks of storage and decreased the following week. Fully ripe fruit stored for two weeks had more total sugars than after one week of storage. In contrast, the ascorbic acid content of pink tomato

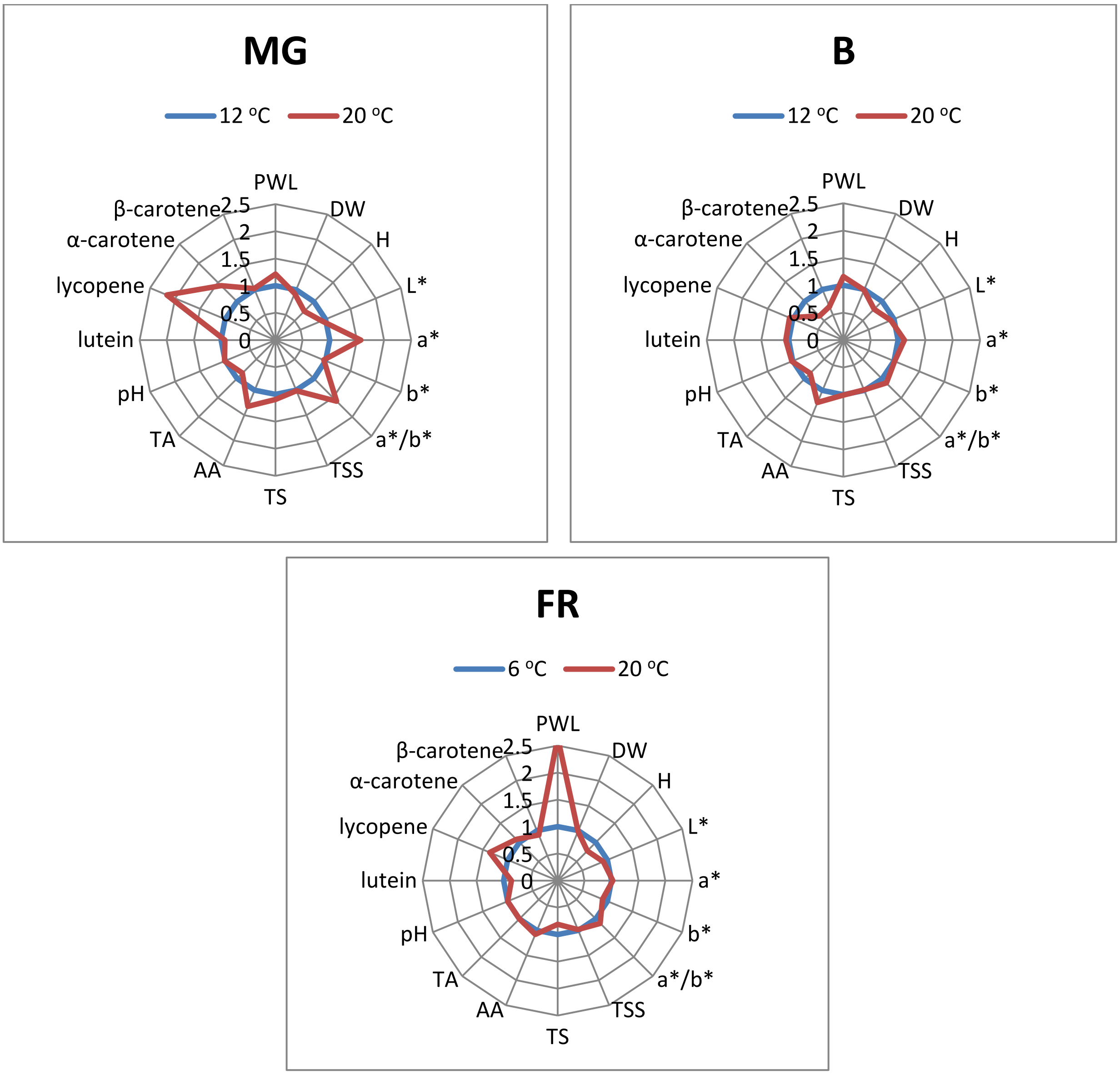

Fig. 2. Influence of storage temperature on selected quality parameters of the fruits with different degrees of maturity: mature green (MG), breaker (B) and fully ripe (FR) of pink tomato cultivar 'Tomimaru Muchoo'

fruit increased during storage, regardless of the combination. Total acidity increased only in stored fully ripe fruit and decreased during storage of both mature green and breaker fruit. In contrast, cell juice pH in all fruits increased during storage. The content of lutein and α- and β-carotene decreased during storage of pink tomato fruits, and lycopene was the highest in fruits that were ripe after one week of storage (Fig. 1).

Higher storage temperature (20 °C) significantly increased the loss of fresh weight of pink tomato fruit, more than the temperature of 12 °C applied to mature green and breaker fruit storage and 6 °C to fully ripe fruit. The higher temperature reduced the dry weight content during the storage of mature green-pink tomato fruit. Fruit firmness was lower when stored at higher temperatures, regardless of fruit maturity. Fruit

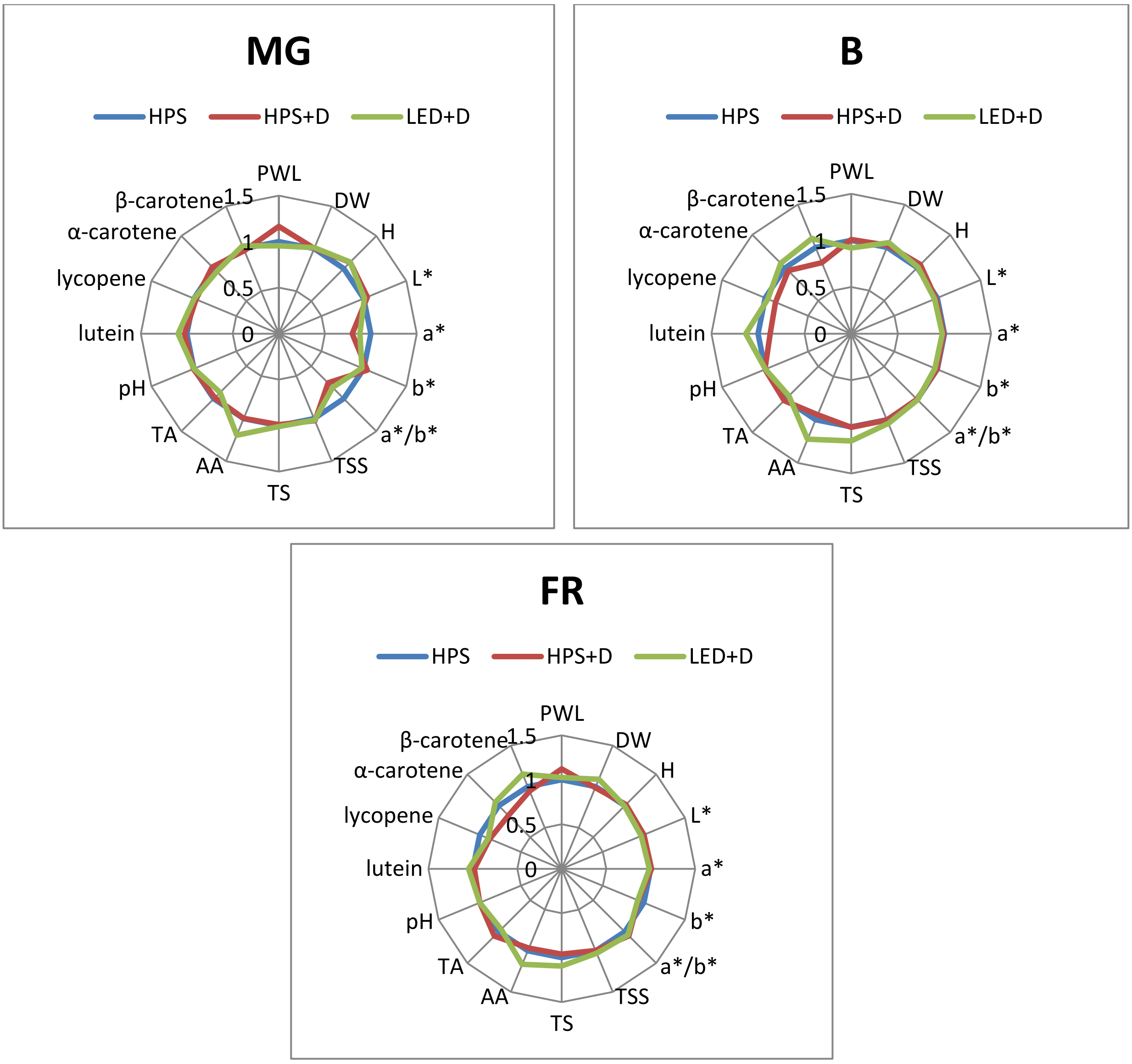

Fig. 3. Influence of growing conditions on selected quality parameters of the fruits with different degrees of maturity: mature green (MG), breaker (B) and fully ripe (FR) of pink tomato cultivar 'Tomimaru Muchoo'

color traits, such as the L*, decreased when stored at a higher temperature compared to fruit stored at a lower temperature. On the other hand, the parameter a* was higher for mature green and breaker fruits stored at the higher temperature, which was not found for stored fully ripe fruits, which had a lower proportion of yellow peel color (b*) at a storage temperature of 20 °C, compared to the color of fully ripe fruits stored at 6 °C.

In all fruits stored at a higher temperature, the a*/b* index increased. Higher storage temperature increased TSS and TS content in mature green tomato fruits. In contrast, the opposite results were obtained for breaker and fully ripe fruits stored at higher temperatures, where there was more TSS and TS especially in fully ripe fruits stored at the lower temperature than at the higher temperature. More ascorbic acid was found in fruit stored at a higher temperature compared to fruit stored at a lower temperature, regardless of ripeness. At the same time, acidity decreased, and the pH of tomato cell juice increased at higher storage temperatures. Mature green and fully ripe fruits had less lutein at the higher storage temperature, and breaker fruits stored at the higher temperature contained less α- and β-carotene. Moreover, fully ripe fruit stored at 20 °C had less β-carotene than at 6 °C. In contrast, tomato fruits stored at a higher temperature had more lycopene than those stored at a lower temperature (Fig. 2).

When comparing the average results for pink tomato fruit stored at the three stages of maturity, there was a significant effect of the cultivation conditions studied on the post-harvest quality of the fruit. In analyzing the sodium-lamp-lighted crop as a control, there was a higher content of dry weight, TSS, TS, AA, and β-carotene, as well as a higher content of TSS and lutein in the stored breaker and fully ripe fruit from the LED-lamp-lighted crop grown under diffusion glass, and higher content of TSS and lutein in the mature green fruit from this combination. Mature green fruits from this combination were also firmer than those from the control. In contrast, fully ripe fruit from the control had a higher lycopene concentration than fully ripe fruit from the HPS+D and LED+D combinations. Fruits from the plants irradiated by sodium lamps, where diffusion glass was used to cover the roof slope, stored at the mature green and breaker fruit stages, showed higher hardness than those from the control. Mature green fruit from HPS+D, when stored, had a lower proportion of red color, a lower a*/b* ratio, lower cell juice pH, and breaker and fully ripe fruit contained less AA, breaker fruit also contained less β-carotene than control fruit (Fig. 3). Pink tomato fruits grown with LED lighting and under diffusion glass (LED+D) were characterized by a significantly higher TS, vitamin C and β carotene content than fruits from the combinations HPS and HPS+D (Fig. 3).

DISCUSSION

In the current experiment, a number of changes related to the quality of tomato fruits resulting from storage conditions, the stage of harvest ripeness and the length of the storage period were observed. However, the literature on the effect of storage conditions on the quality of tomato fruits mainly concerns the storage of red varieties, not the pink ones. It can be generally stated that various authors indicate that the quality of tomato fruits depends on many factors, including post-harvest factors, which is in agreement with the current findings. According to Chiesa et al. [1998], Getinet et al. [2008], and Klunklin and Savage [2017], the content of nutrients and bioactive compounds, such as lycopene, β-carotene, ascorbic acid in tomato fruits depends primarily on the variety and growth factors, such as temperature, light, humidity, fertilization, but also on storage conditions. In this experiment, tomato fruits, regardless of the stage of harvest maturity, showed a higher physiological weight loss and lower hardness in the subsequent weeks of storage but were characterized by a higher content of ascorbic acid and a higher pH value of the cell juice. Mature green and breaker fruits also showed a decrease in TA content during storage. Tomato fruits stored at full maturity at the temperature of 20 °C showed a higher ratio of the a*/b* color parameters, contained the most ascorbic acid and lycopene, and had a higher pH of the cell juice than ripe fruits stored at 6 °C. Similar results were obtained by Getinet et al. [2008]. The current study also found that fruits harvested at the mature green and breaker stage and stored at 20 °C showed higher physiological losses of fresh mass and began to soften faster than those stored at 12 °C. On the other hand, at 20 °C their color changed faster, and the color index (a*/b*) and AA concentration, pH of the cell juice increased, while TA concentration decreased. According to Brandt et al. [2006], a higher a*/b* ratio in tomato fruits indicates a higher lycopene content in the fruits. In the fruits harvested at the mature green stage, stored at 20 °C, it was found that the content of lycopene and other carotenoids, such as α-carotene and lutein, as well as TSS and TS, increased. According to Diretto et al. [2020], an increase in β-carotene content also results in a higher ABA content, which, in turn, affects the ripening of tomato fruits and their shelf life. In the case of fully ripe fruits stored for two weeks at 6 °C, the current experiment showed less physiological fresh weight loss compared to fully ripe fruits stored at 20 °C. The study also found higher fruit hardness and higher TSS, TS, lutein and β-carotene contents compared to those stored for one week. These results are in accordance with Selahle et al. [2014], who found that during ripening, the content of monosaccharides, which are the most important contributors to TSS content, increases in tomato fruits. According to the literature, the observed changes in TSS components in the current study may result from changes in the glucose-fructose ratio and organic acids in tomatoes after harvest, while TSS has been noted as an important indicator of tomato flavor [Javanmardi and Kubota 2006].

The results obtained from the storage of fruits of pink tomato cv. 'Tomimaru Muchoo F_1' originating from winter production, indicates the positive effect of assimilation light with LED lamps in a combination of top and inter-row light with the use of diffusion glass to cover the greenhouse roof on the post-harvest quality of fruits and their storage, compared to lighting with traditional sodium lamps regardless of the use of diffusion glass. Stored fruit at both the breaker and fully ripe stage after LED-lamp irradiation and cultivation under diffusion glass showed higher dry weight, TSS, TS, AA, and β-carotene contents. Moreover, higher TSS and lutein contents were found in mature green fruit stored in this combination. Fruits from HPS cultivation, where diffusion glass was used to cover the roof slope, stored at the maturity stage of mature green and breaker fruit, had higher firmness than the fruits from HPS cultivation without the use of diffusion glass to cover the roof. Variations in light intensity and quality, direction and duration activate plant responses that are controlled and carried out by specific photoreceptors [Kami et al. 2010]. Light is an important environmental factor that regulates the activity of biochemical pathways involved in biochemical metabolism during tomato ripening [Wang et al. 2021]. According to Wang et al. [2022 a,b], the use of LEDs to improve lighting conditions during tomato cultivation is an effective method to improve tomato fruit quality. Dong et al. [2019] showed that, compared to white light, a combination of red and blue (R : B, 3 : 1) LEDs increases the content of TSS, glucose, fructose and sucrose in tomato fruit through the accumulation of proteins associated with glucose metabolic pathways. According to Dannehl et al. [2021] and Li et al. [2021], compared to lighting using high-pressure sodium lamps, LEDs significantly increase lycopene content in tomato fruit. High-intensity blue LED light can stimulate the antioxidant system in tomato fruit, increasing ascorbic acid content, among others [Zushi et al. 2020]. On the other hand, according to Dhakal et al. [2014] and Panjai et al. [2019], continuous red LED lighting significantly promotes an increase in the content of free amino acids, lycopene, β-carotene, phenolic acids and flavonoids in tomato fruit after harvest. Kong et al. [2020] also reported that blue LED light can significantly increase the content of TSS, lycopene and phenolic compounds in tomato fruit after harvest. According to Olle and Alsina [2019], among other things, blue and red light increase ascorbic acid, while the concentration of pigments increases under green, blue and red light, and the sugar content of plants increases under green, blue and red light. In the current study, 'Tomimaru Muchoo' fruits harvested fully ripe during storage contained more vitamin C than stored fruit harvested at the mature green and breaker stage. Moreover, ripe fruit from the LED+D combination had more vitamin C during storage than fruits from the other maturity stages. Ntagkas et al. [2019] showed that AA level significantly increases when tomato fruit ripens under light.

Tomatoes require the right amount and quality of light for proper growth and development. The use of diffusion glass to cover the roof slopes of production greenhouses, among other things, influences a better distribution of sunlight in the plant canopy, which optimizes the use of light in photosynthesis [Holsteens et al. 2020]. Efficient year-round production of tomatoes can be carried out under controlled greenhouse conditions in any climate zone, even when there is insufficient solar radiation DLI (daily light integral) supplemented with artificial light [Paponov et al. 2019, Paucek et al. 2020]. Both diffusion glass and various artificial light sources and methods of plant lighting affect tomato growing conditions. Reports by Arah et al. [2015] and Affandi et al. [2022] confirm that growing conditions affect the post-harvest quality of tomato fruit and storage.

CONCLUSIONS

The lighting of pink tomato plants cv. 'Tomimaru Muchoo' with LED diodes in combination with diffused glass used in the greenhouse resulted in extended storability of the fruit and also better quality after harvest compared to the fruit from plants illuminated with HPS lamps and the fruit from plants illuminated with HPS lamps in combination with diffused glass. Extending the storage period of pink tomato fruit cv. 'Tomimaru Muchoo', regardless of the stage of harvest maturity and lighting method, resulted in greater loss of physiological mass and lower fruit hardness but increased ascorbic acid content and increased the pH of the cell juice. Storing tomato fruit at 20 °C resulted in higher physiological loss of fresh mass and lower fruit hardness compared to the fruit stored at lower temperatures (12 °C for mature green and breaker fruits and 6 °C for fully ripe fruits). The temperature of 20 °C used during fruit storage caused, regardless of the method of lighting in the greenhouse, faster color development of tomato fruit and an increase in TSS, as well as a higher concentration of ascorbic acid and carotenoids in the fruit compared to the lower temperatures applied.

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REFERENCES

Aćamović-Djoković, G., Pavlović, R., Mladenović, J., Djurić, M. (2011). Vitamin C content of different types of lettuce varieties. Acta Agric. Serb., 17, 83–89.

Affandi, F.Y., Pijnenburg, Ch., Verdonk, J.C., Woltering, E.J., Schouten, R.E. (2022). Growth temperature influences postharvest quality and cold tolerance of green harvested dwarf tomatoes during storage. Front. Sustain. Food Syst., 6, 876597. https://doi.org/10.3389/fsufs.2022.876597

Al-Gaadi, K.A., Zeyada, A.M., Tola, E., Alhamdan, A.M., Ahmed, K.A.M., Madugundu, R., Edrris, M.K. (2024). Impact of storage conditions on fruit color, firmness and total soluble solids of hydroponic tomatoes grown at different salinity levels. Appl. Sci., 14, 6315. https://doi.org/10.3390/app14146315

Appolloni, E., Orsini, F., Pennisi, G., Durany, X.G., Paucek, I., Gianquinto, G. (2021). Supplemental LED lighting effectively enhances the yield and quality of greenhouse truss tomato production: results of a meta-analysis. LED lighting for greenhouse tomato: a review. Front. Plant Sci., 12, 596927. https://doi.org/10.3389/fpls.2021.596927

Arah, I.K., Amaglo, H., Kumah, E.K., Ofori, H. (2015). Preharvest and postharvest factors affecting the quality and shelf life of harvested tomatoes: a mini review. Int. J. Agron., 478041. https://doi.org/10.1155/2015/478041

Brandt, S., Pék, Z., Barna, É., Lugasi, A., Helyes, L. (2006). Lycopene content and colour of ripening tomatoes as affected by environmental conditions. J. Sci. Food Agric., 86, 568–572. https://doi.org/10.1002/jsfa.2390

Chiesa, L., Diaz, L., Cascone, O., Pañak, K., Camperi, S., Frezza, D., Fraguas, A. (1998). Texture changes on normal and long-shelf life tomato (*Lycopersicon esculentum* Mill.) fruit ripening. Acta Hortic., 464, 488.

Dannehl, D., Schwend, T., Veit, D., Schmidt, U. (2021). Increase of yield, lycopene, and lutein content in tomatoes grown under continuous PAR spectrum LED lighting. Front Plant Sci., 12, 611236. https://doi.org/10.3389/fpls.2021.611236

Dhakal, R., Baek, K.H., 2014. Metabolic alternation in the accumulation of free amino acids and γ-aminobutyric acid in postharvest mature green tomatoes following irradiation with blue light. Hortic. Environ. Biotechnol., 55, 36–41. https://doi.org/10.1007/s13580-014-0125-3

Diretto, G., Frusciante, S., Fabbri, C., Schauer, N., Busta, L., Wang, Z., Matas, A.J., Fiore, A., Rose, J.K.C., Fernie, A.R., Jetter, R., Mattei, B., Giovannoni, J., Giuliano, G. (2020). Manipulation of β-carotene levels in tomato fruits results in increased ABA content and extended shelf life. Plant Biotechnol. J., 18, 1185–1199. https://doi.org/10.1111/pbi.13283

Dong, F., Wang, C.Z., Sun, X.D., Bao, Z.L., Dong, C., Sun, C.H, et al. (2019). Sugar metabolic changes in protein expression associated with different light quality combinations in tomato fruit. Plant Growth Regul., 88, 267–82. https://doi.org/10.1007/s10725-019-00506-1

D'Souza, C., Yuk, H.G., Khoo, G.H., Zhou, W. (2015). Application of light-emitting diodes in food production, postharvest preservation, and microbiological food safety. Compreh. Revi. Food Sci. Food Safety, 14, 719–740.

Dueck, T., Janse, J., Li, T., Kempkes, F., Eveleens, B. (2012). Influence of of low-haze diffuse glass on the growth and production of tomato. Acta Hortic., 956, 75–82.

Garbowicz, K., Liu, Z., Alseekh, S., Tieman, D., Taylor, M., Kuhalskaya, A. (2018). Quantitative trait loci analysis identifies a prominent gene involved in the production of fatty acid-derived flavor volatiles in tomato. Mol. Plant, 11, 1147–65. https://doi.org/10.1016/j.molp.2018.06.003

Getinet, H., Seyoum, T., Woldetsadik, K. (2008). The effect of cultivar, maturity stage and storage environment on quality of tomatoes. J. Food Eng., 87, 467–478.

Gómez, C., Mitchell, C.A. (2016). In search of an optimized supplemental lighting spectrum for greenhouse tomato production with intra-canopy lighting Acta Hortic., 1134, 57–62.

Gormley, T.R., Maher, M.J. (1990). Tomato fruit quality-an interdisciplinary. Prof. Hortic., 4, 7–12.

Guo, X., Hao, X., Khosla, S., Kumar, K.G.S., Cao, R., Bennett, N., 2016. Effect of LED inter-lighting combined with overhead HPS light on fruit yield and quality of year-round sweet pepper in commercial greenhouse. Acta Hortic., 1134, 71–78.

Hemming, S., Dueck, T., Janse, J., van Noort, F. (2008). The effect of diffuse light on crops. Acta Hortic., 801, 1293–1300.

Holsteens, K., Moerkens, R., Bram Van de Poel, B., Vanlommel, W. (2020). The effect of low-haze diffuse glass on greenhouse tomato and bell pepper production and light distribution properties. Plants, 9, 806. https://doi.org/10.3390/plants9070806

Javanmardi, J., Kubota, C. (2006). Variation of lycopene, antioxidant activity, total soluble solids and weight loss of tomato during postharvest storage. Postharvest Biol. Technol., 41, 151–155. https://doi.org/10.1016/j.postharvbio.2006.03.008

Khairia, A.N., Falaha, M.A.F., Suyantohadia, A., Takahashib, N., Nishina, H. (2015). Effect of storage temperatures on color of tomato fruit (*Solanum lycopersicum* Mill.) cultivated under moderate water stresstreatment. Agric. Agric. Sci. Proc., 3, 178–183.

Kami, C., Lorrain, S., Hornitschek, P., Fankhauser, C. (2010). Light-regulated plant growth and development. Curr. Top. Dev. Biol., 91, 29–66.

Kim, H.-J., Yang, T., Choi, S., Wang, Y.-J., Lin, M.-J., Liceaga, A.M. (2020). Supplemental intracanopy far-red radiation to red LED light improves fruit quality attributes of greenhouse tomatoes. Sci. Hortic., 261, 108985. https://doi.org/10.1016/j.scienta.2019.108985

Kim, Y.X., Son, S., Lee, S., Jung, E., Lee, Y., Sung, J., Lee, C. (2021). Combined effects of nutrients × water × light on metabolite composition in tomato fruits (*Solanum lycopersicum* L.). Plants, 10, 1437. https://doi.org/10.3390/plants10071437

Klunklin, W., Savage, G. (2017). Effect on quality characteristics of tomatoes grown under well-watered and drought stress conditions. Foods, 6, 56. https://doi.org/10.3390/foods6080056

Kong, D.H., Zhao, W.T., Ma, Y., Liang, H., Zhao, X.Y. (2020). Effects of light-emitting diode illumination on the quality of fresh-cut cherry tomatoes during refrigerated storage. Int. J. Food Sci. Tech., 56, 2041–2052. https://doi.org/10.1111/ijfs.14836

Kumar, K.G.S., Hao, X., Khosla, S., Guo, X., Bennett, N. (2016). Comparison of HPS lighting and hybrid lighting with top HPS and intra-canopy LED lighting for high-wire mini-cucumber production. Acta Hortic., 1134, 111–118.

Lenucci, M.S., Cadinu, D., Taurino, M., Piro, G., Dalessandro, G. (2006). Antioxidant composition in cherry and high-pigment tomato cultivars. J. Agric. Food Chem., 54, 2606–2613. https://doi.org/10.1021/jf052920c

Li, J., Di, T., Bai, J. (2019). Distribution of volatile compounds in different fruit structures in four tomato cultivars. Molecules, 24, 2594. https://doi.org/10.3390/molecules24142594

Li, T., Heuvelink, E., Dueck, T.A., Janse, J., Gort, G., Marcelis, L.F. (2014a). Enhancement of crop photosynthesis by diffuse light: quantifying the contributing factors. Ann. Bot., 114, 145–156. https://doi.org/10.1093/aob/mcu071

Li, T., Heuvelink, E., van Noort, F., Kromdijk, J., Marcelis, L.F.M. (2014b). Responses of two *Anthurium* cultivars to high daily integrals of diffuse light. Sci. Hortic., 179, 306–313. https://doi.org/10.1016/j.scienta.2014.09.039

Li, Y., Liu, C., Shi, Q.H., Yang, .FJ., Wei, M. (2021). Mixed red and blue light promotes ripening and improves quality of tomato fruit by influencing melatonin content. Environ Exp Bot., 185, 104407. https://doi.org/10.1016/j.envexpbot.2021.104407

Liu, H.R., Meng, F.L., Miao, H.Y., Chen, S.S., Yin, T.T., Hu, S.S. (2018). Effects of postharvest methyl jasmonate treatment on main health-promoting components and volatile organic compounds in cherry tomato fruits. Food Chem., 263, 194–200. https://doi.org/10.1016/j.foodchem.2018.04.124

Ntagkas, N., Woltering, E., Bouras, S., de Vos, R.C.H., Dieleman, J.A., Nicole, C.C.S., Labrie, C., Marcelis, L.F.M. (2019). Light-induced vitamin C accumulation in tomato fruits is independent of carbohydrate availability. Plants, 8, 86, https://doi.org/10.3390/plants8040086

Olle, M., Alsina, I. (2019). Influence of wavelength of light on growth, yield and nutritional quality of greenhouse vegetables Proc. Latvian Acad. Sci., sec. B, 73, 1–19. https://doi.org/10.2478/prolas-2019-0001

Olle, M., Viršile, A. (2013). The effects of light-emitting diode lighting on greenhouse plant growth and quality. Agric. Food Sci., 22, 223–234. https://doi.org/10.23986/afsci.7897

Panjai, L., Noga, G., Hunsche, M., Fiebig, A. (2019). Optimal red light irradiation time to increase health-promoting compounds in tomato fruit postharvest. Sci Hortic., 251, 189–196. https://doi.org/10.1016/j.scienta.2019.03.019

Paponov, M., Kechasov, D., Lacek, J., Verheul, M.J., Paponov, I.A. (2019). Supplemental light-emitting diode inter-lighting increases tomato fruit growth through enhanced photosynthetic light use efficiency and modulated root activity. Front Plant Sci., 10, 1656. https://doi.org/10.3389/fpls.2019.01656

Paucek, I., Pennisi, G., Pistillo, A., Appolloni, E., Crepaldi, A., Calegari, B. (2020). Supplementary LED interlighting improves yield and precocity of greenhouse tomatoes in the Mediterranean. Agronomy, 10, 1002. https://doi.org/10.3390/agronomy10071002

Rab, A., Rehman, H., Sajid, M., Nawab, K., Ali, K. (2013). Harvest stages and pre-cooling influence the quality and storage life of tomato fruit. J. Anim. Plant Sci., 23, 1347–1357.

Selahle, M.K., Sivakumar, D., Soundy, P. (2014). Effect of photo-selective nettings on post-harvest quality and bioactive compounds in selected tomato cultivars. J. Sci. Food Agric., 94, 2187–2195. https://doi.org/10.1002/jsfa.6536

Wang, S., Jin, N., Jin, L., Xiao, X., Hu, L., Liu, Z., Yu, J. (2022a). Response of tomato fruit quality depends on period of LED supplementary light. Front. Nutr., 9, 833723.

Wang, S., Jin, N., Jin, L., Xiao, X., Hu, L., Liu, Z., Wu, Y., Xie, Y., Zhu, W., Lyu, J., Yu, J. (2022b). Response of tomato fruit quality depends on period of LED supplementary light. Front. Nutr., 9, 833723. https://doi.org/10.3389/fnut.2022.833723

Wang, W., Liu, D.X., Qin, M., Xie, Z.B., Chen, R.Y., Zhang, Y.T. (2021). Effects of supplemental lighting on potassium transport and fruit coloring of tomatoes grown in hydroponics. Int. J. Mol. Sci., 22, 2687. https://doi.org/10.3390/ijms22052687

Zeng, X., Wang, L., Fu, Y., Zuo, J., Li, Y., Zhao, J., Cao, R., Li, J. (2022). Effects of methyl salicylate pre-treatment on the volatile profiles and key gene expressions in tomatoes stored at low temperature Front. Nutr., 9, 1018534. https://doi.org/10.3389/fnut.2022.1018534

Zhang, Y.T., Zhang, Y.Q., Yang, Q.C., Tao, L.I. (2019). Overhead supplemental far-red light stimulates tomato growth under intra-canopy lighting with LEDs. J. Integr. Agric., 18, 62–69. https://doi.org/10.1016/s2095-3119(18)62130-6