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The Effect of Visible Light on the Postharvest Life of Tomatoes (*Solanum lycopersicum* L.)

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Abstract: Tomatoes (*Solanum lycopersicum* L.) are widely cultivated and consumed, but ripening should be carried out in controlled storage conditions to extend their shelf life and avoid economic losses. The aim of this study was to investigate the effects of visible artificial light on the ripening and quality of fresh market tomatoes stored at a low temperature and high humidity. The postharvest performance with respect to the ripening of organically grown tomatoes in the Toscano cultivar, with a long storage life, was studied in the presence and the absence of visible LED light. The maturation kinetics of the tomatoes was modeled using the Power Law equation. Results showed that tomatoes stored in the presence of light exhibited an increased respiration rate and a faster preclimacteric phase. Lycopene content, total soluble solids, and maturity index increased in the presence of light. Hence, light increased the postharvest ripening of tomatoes, affecting their shelf life.

Keywords: carbon dioxide; ethylene; fruit quality parameters; kinetics; LED light

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1. Introduction

Tomato fruit (*Solanum lycopersicum* L.) is widely cultivated and consumed worldwide, with an annual production in 2019 of 180 million tons, equivalent to USD 90 billion [1]. More than 80% of tomatoes are processed, producing tomato juice, sauce, paste, puree, and ketchup. Tomatoes are rich in organic acids, reducing sugars, pectin, and carotenoids such as lycopene with antioxidant activity [2,3]. Lycopene is the most active antioxidant molecule in nature, with tomatoes and tomato products being the major source of this health-promoting compound. Due to the importance of tomatoes in the human diet, it is recommended to consume 70–90 g daily or 25–32 kg per year of tomatoes for an adult human being [4].

Nowadays, consumers are becoming more aware of environmental problems and health risks resulting from the intensive use of agrochemicals by conventional agriculture [5]. As the sustainability of conventional agricultural production systems is questioned, sustainable farming practices such as organic growth systems are rapidly emerging in many countries with the dynamic performance of the organic food market [6]. Therefore, studies concerning the nutritional value and postharvest properties of organically grown plant products are receiving more attention now.

Fresh market tomato fruits are highly perishable during storage, as they are susceptible to rot caused by fungi such as *Alternaria alternata*, *Botrytis cinerea*, and *Rhizopus stolonifera*. Hence, they should be ripened in controlled storage conditions to extend their shelf life [7].

Detrimental effects on the quality of fresh fruits and vegetables may result in an economic loss of 55% of the total production [8,9].

Ethylene is a plant hormone that stimulates chlorophyll loss, enhances carotenoid synthesis, promotes tissue softening, and contributes to taste and flavor development by stimulating fruit ripening [10]. Thus, ethylene is a key factor in the fruit ripening process. Several technologies are reported to prolong the shelf life of fruits: (1) fruit storage at a lower temperature and higher humidity; (2) a controlled or modified atmosphere to maintain the oxygen content at a low level; (3) treatment with silver thiosulfate; (4) blocking the ethylene receptor with 1-methylcyclopropene (1-MCP); and (5) oxidation of ethylene to carbon dioxide by ozone, potassium permanganate, titanium dioxide, and vacuum ultraviolet light [11–14]. Conversely, tomatoes stored in supermarket facilities are often exposed for about 10–12 h per day to lighting by fluorescent lamps to catch the consumers' attention for purchase [15]. Studies focused on the effects of visible light on tomatoes' shelf life have not addressed the ripening time or related attributes.

Light is known to influence many important processes related to plant development. Regarding fruit, light drives photosynthesis and photomorphogenic processes. Although fruits mainly depend on assimilation products coming from the leaves to grow and mature, their own photosynthesis processes can provide some additional carbon gain for net photosynthesis, being particularly important for seed development [16,17]. Additionally, light interacts with photoreceptors in the tomato flesh and promotes a cascade of downstream signaling events that modulates fruit development at both the genetic and hormonal levels [18,19].

The aim of this study was to investigate the effects of visible artificial light on the ripening and quality of organically grown tomatoes at low-temperature and high-humidity storage conditions.

2. Materials and Methods

2.1. Plant Material

The influence of lighting was studied in tomatoes (*Solanum lycopersicum* L.) in the Toscano cultivar, which have a long storage life. The tomato plants were cultivated organically in a commercial field plot in Oro Verde (Chillán, Chile). Fruits were harvested at the breaker stage at two different dates (4 April 2021 and 21 April 2021) for treatment in the presence (group 1) and in the absence (group 2) of light. Fruits with smooth cuticles and free of any visible damage or maceration were immediately transported to the laboratory and sorted for uniformity according to size and color. Tomatoes were dipped for 15 min in a solution of 0.1% (*m/v*) sodium benzoate and 0.1% (*m/v*) potassium sorbate, washed with sterile demineralized water, and air-dried in a laminar flow hood, followed by storage overnight in the dark at room temperature.

2.2. Storage Conditions

First, 36 fruits were randomly picked from a lot of 70 fruits and treated by light-emitting diodes (LEDs). In addition, 6 randomly chosen fruits were used to find and compare the properties of the raw materials. This procedure was repeated for the second group of tomatoes treated in darkness. The treated fruit were stored at 12 °C and 88% relative humidity for 12 days (group 1) and 17 days (group 2) in hermetically sealed 10 L glass desiccators located within a climate incubator (BJPX-A500 II—Biobase Biodustry, Shandong Co. Ltd., Shandong, China). The lighted tomatoes were exposed to an illuminance of 12.000 lx using 31 LED lamps (LED T5, WT5-10-65/111, 220 V—50 Hz, 10 W) for 12 h per day, installed closely parallel to each other and fixed to the incubator walls about 10 cm away from the desiccators.

During storage of the tomato fruit, the concentrations of ethylene, carbon dioxide, and oxygen were measured daily. Every two or three days, fruit samples were withdrawn to assess the postharvest attributes. Each desiccator comprised an experimental unit with

three fruits and six sampling point units over the storage time per treatment. Two replicates per treatment were applied.

2.3. Gas Composition

A volume of 1.0 mL of the headspace atmosphere from the desiccators was withdrawn each 24 h using a syringe and injected into a Perkin Elmer Clarus 500 gas chromatography (GC) system (Perkin Elmer Inc., Shelton, CT, USA) to determine the CO_2 and O_2 concentrations. The gas chromatograph was equipped with a thermal conductivity detector (TCD) operating at 200 °C and a Carboxen-1000 packed column (60–80 mesh) 4.5 m of length and with a 2.1 mm internal diameter. Helium was used as a carrier gas with a flow rate of 30 mL min^{-1}. Separations started at an initial oven temperature of 40 °C. Then, the temperature was increased to 170 °C at 4 °C min^{-1} with a holding time of 6 min. Results were expressed as mg L^{-1} O_2 and CO_2 and were the mean ± standard deviation of two measurements for each of the replicates. Another 2.5 mL sample of the headspace atmosphere was used to quantify the ethylene concentration by GC, equipped with a flame ionization detector (FID) operating at 250 °C and using a 60 m VOCOL^{TM} capillary column (internal diameter of 0.53 mm; 3.0 µm film thickness). The injector temperature was fixed at 200 °C. Helium was used as a carrier gas at a flow rate of 7.0 mL min^{-1}. The temperature program started at an initial oven temperature of 40 °C, and then the temperature was increased to 170 °C at 2 °C min^{-1} and held at 170 °C for 5 min. The results were expressed in µg L^{-1} of ethylene and were the mean ± standard deviation of two measurements for each replicate.

The molecular oxygen consumption (mg kg^{-1} h^{-1}) due to respiration was calculated according to Equation (1):

$$[O_2]_c = \frac{([O_2]_0 - [O_2]_t)\cdot(DV - \sum FV)}{(\sum m)\cdot(t_t - t_0)}. \quad (1)$$

Carbon dioxide production (mg kg^{-1} h^{-1}) due to respiration was calculated according to Equation (2):

$$[CO_2]_p = \frac{([CO_2]_t - [CO_2]_0)\cdot(DV - \sum FV)}{(\sum m)\cdot(t_t - t_0)}. \quad (2)$$

Ethylene production (µg kg^{-1} h^{-1}) due to fruit ripening was calculated with Equation (3):

$$[C_2H_4]_p = \frac{([C_2O_4]_t - [C_2O_4]_0)\cdot(DV - \sum FV)}{(\sum m)\cdot(t_t - t_0)}, \quad (3)$$

where $[O_2]_0$ and $[O_2]_t$ are the oxygen concentrations within the desiccator (mg L^{-1}) at t = 0 and t = t, respectively, $[CO_2]_0$ and $[CO_2]_t$ are the carbon dioxide concentrations within the desiccator (mg L^{-1}) at t = 0 and t = t, respectively, $[C_2H_4]_0$ and $[C_2H_4]_t$ are the ethylene concentrations within the desiccator (µg L^{-1}) at t = 0 and t = t, respectively, DV is the internal desiccator volume (L), ΣFV is the sum of the volumes (L) of each fruit, Σm is the sum of the mass (kg) of each fruit, t_t is the time t (h), and t_0 is the time 0 (h).

2.4. Tomato Quality Attributes

The weight of each fruit was recorded using an electronic balance (XD 6200 D, Precisa Instruments AG, Dietikon, Switzerland) with 0.1 g of precision. Weight loss (WL) was expressed as the percentage of the original weight lost. The polar and equatorial diameters of individual fruit were measured using a digital vernier caliper (150 × 0.05 mm; Stanford professional, Truper) with 0.01 mm of precision. Skin color was determined by taking a digital image of a tomato sample within a black box lit by the LED lamps of a Dinolite digital microscope (AF 4515T-FUW, Dunwell Tech. Inc., Torrance, CA, USA), with a minimum enlargement of 8.6 mm, 6th level LED brightness, Axi illuminance, EDR, and a 1280 × 1024 pixel resolution, coupled to a camera operating at 128 lightness, 16 contrast, 0 redness, greenness, and blueness, 16 saturation, 1 sharpness, and 16 gamut. The redness

(a*), yellowness (b*), and lightness (L*) coordinates of the CIE color space were quantified from digital images using Munsell Conversion software (version 6.5.9), and the hue (h), chroma (C), and color difference (ΔE) were calculated [20]. The moisture content of the tomato samples was determined by gravimetry using the A.O.A.C. method (934.06) [21]. The determination of the total soluble solids (TSS) was performed according to the A.O.A.C. method (932.12) using a BOECO 32,195 digital refractometer (Hamburg, Germany) [21]. The titratable acidity (TA) was determined by titration with 0.1 N NaOH until a pH of 8.2 according to the A.O.A.C. method (942.15) and expressed as a percentage of citric acid equivalent [21]. The maturity index (MI) was expressed as the ratio between the total soluble solids and titratable acidity. The lycopene (LP) content, expressed in mg lycopene per kg dry weight of tomato, was determined according to the method proposed by Fish et al. [22], with minor modifications as described in [23]. Tomato quality attributes were measured in triplicate for each experimental unit.

2.5. Kinetics

Each desiccator operated as a constant-volume batch reactor with the reactant (A) being consumed (Equation (4)) or quality attribute (P) decreasing (Equation (5)):

$$-\frac{d[A]}{dt} = k \cdot [A]^n \quad (4)$$

$$-\frac{dP}{dt} = k \cdot P^n, \quad (5)$$

Alternatively, product (B) would be formed (Equation (6)), or the quality attribute (G) would be generated (Equation (7)):

$$\frac{d[B]}{dt} = k \cdot [B]^n \quad (6)$$

$$\frac{dG}{dt} = k \cdot G^n, \quad (7)$$

where k stands for the reaction constants, n is the order of the reaction, and t refers to time. Equations (4)–(7) represent the Power Law model.

The differential method of data analysis was used to evaluate the differential rate equations (Equations (4)–(7)) by taking the logarithms of each rate equation for the respiration of the ripening components and the quality attributes, yielding the order of reaction n from the slope and the reaction constant k from the intercept [24]. After approximating n to an integer value, the reaction constant k was calculated by an iteration procedure, comparing the experimental and model data while using as the iteration criterion the slope between these data, which was nearly one. The coefficient of determination (R^2) was calculated as a measure to assess the ability of the Power Law model to predict the experimental data using Excel (version 2210) software (Microsoft 365).

2.6. Experimental Design and Statistical Analyses

A completely randomized block design with two treatments (in the presence and in the absence of light irradiation) and three blocks (day 0, day 6, and day 12) was used with three observations of the tomatoes' properties as the dependent variables of each block [25].

The Wilcoxon rank-sum test was used ($\alpha = 0.05$) to compare two independent samples of raw material (day 0) harvested at different times for whether their population mean ranks differed for the searched tomato properties. Friedman's test was carried out ($\alpha = 0.05$) for finding any difference in treatments for day 6 and day 12 by assessing the tomato properties. Spearman's rank correlation test was performed ($\alpha = 0.05$) to measure the degree of association between the dependent variables (tomato properties) and independent variable (time) [26]. Statistics were analyzed by using InfoStat © statistical software, student version 2017 (Universidad Nacional de Córdoba, Argentina).

3. Results and Discussion

3.1. Effect of Light on Preclimacteric Ripening of Tomato Fruit

Concentrations of the oxygen, carbon dioxide, and ethylene species involved in biochemical processes during tomato respiration and ripening from the breaker stage were correlated with time in both the light and dark treatments according to Spearman's test, fitting their parameters with the Power Law model (Table 1).

Table 1. Parameters of the Power Law model for fitting oxygen consumption and carbon dioxide and ethylene evolutions during tomato ripening in light or dark storage conditions, where k stands for the reaction constant, n the order of reaction and R^2 the coefficient of determination.

Compound	With Light			Without Light		
	k	n	R^2	k	n	R^2
O_2	1.3×10^{-7}	3	0.990	1.7×10^{-12}	5	0.985
CO_2	5.3×10^{-1}	0	0.987	3.5×10^{-1}	0	0.878
C_2H_4	8.7×10^{-6}	0	0.930	6.8×10^{-6}	0	0.941

The reaction kinetics of oxygen consumption by the tomatoes was affected by the oxygen concentration in terms of the desiccator's headspace and lighting, as the order of the reaction was of the third and fifth degree with and without light, respectively (Table 1). The remarkable decrease in the reaction constant k for O_2 consumption, together with the increase in the global reaction order until the fifth degree in the absence of light (Table 1), suggests that metabolic processes that consume O_2 may be stimulated by light during tomato fruit ripening in shelf conditions.

Tomato fruit photosynthesis has been shown to respond to light during ripening [27]. These authors studied non-photochemical quenching and photochemical quenching during tomato fruit ripening and found that the greatest separation of non-photochemical quenching among different cultivars occurred in the range of 100–400 µmol m^{-2} s^{-1} for the proton flux density. As the irradiance along our experiment was kept around 180 µmol m^{-2} s^{-1}, changes in photosynthesis and respiration rates in both the presence and absence of light might influence the CO_2 and O_2 compositions of the air samples analyzed to some extent. However, respiration would contribute more to the changes in the gaseous atmosphere of the desiccator's headspace, as photosynthesis would be more restricted to the decreasing green areas of the fruit.

The effect of light on the consumption of oxygen and the evolution of carbon dioxide and ethylene over time can be observed in Figures 1–3.

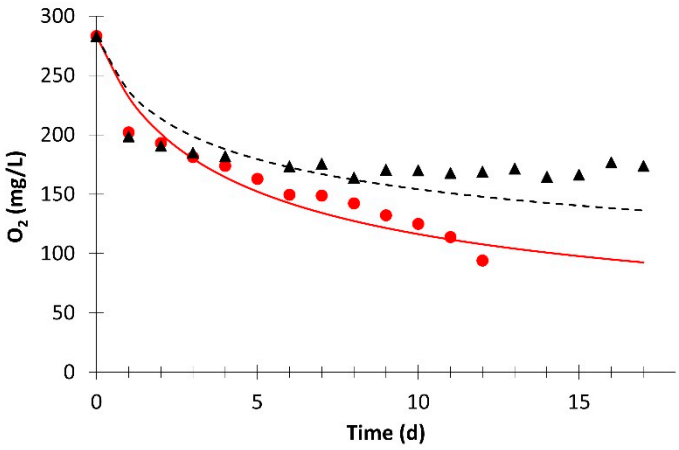

Figure 1. Oxygen consumption during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –).

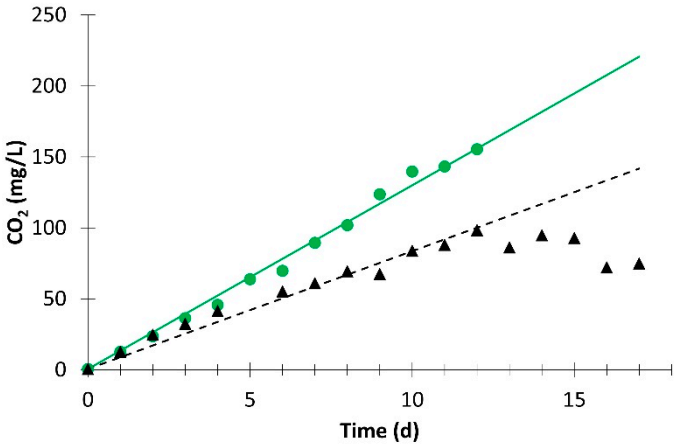

Figure 2. Carbon dioxide evolution during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –).

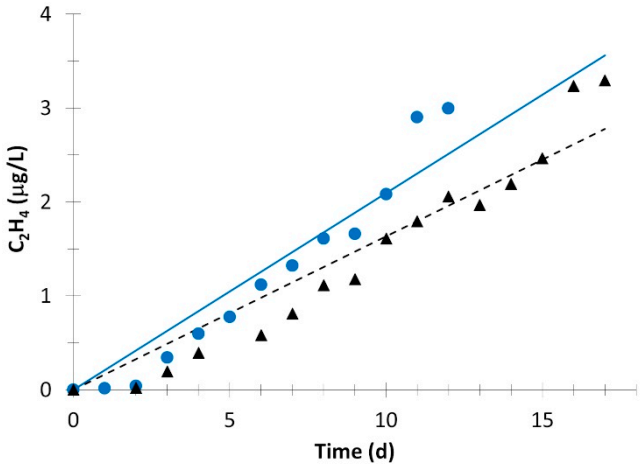

Figure 3. Ethylene evolution during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –).

Oxygen consumption was predicted by a polynomial model of the respiration frequency for tomatoes stored in closed systems [28,29], which agreed with our results. Moreover, light-induced phenomena were irrelevant at the beginning of storage (0–4 d), as the oxygen concentrations were similar with and without lighting. This could be a period of fruit metabolism acclimation to the new exogenous conditions (Figure 1). However, additional oxygen consumption in light was observed after 6 d (Figure 1). This shows the influence of light on the ripening metabolism, which may affect a tomato's shelf life.

The release of carbon dioxide by the fruit increased linearly during the major part of storage (0–12 d) with and without light, in agreement with a linear respiration model [30,31]. In dark storage conditions, the reaction rate constant diminished by 34% compared with light storage (Table 1), with a strong inhibition of CO_2 production after 12 d (Figure 2). This inhibition did not occur in the presence of light.

In this study, the tomatoes were taken at the breaker stage, when an intense flux in energy and the carbon skeleton via primary and secondary metabolisms takes place. Depending on the tomato variety, even before ripening is visible or at the onset of remarkable color changes, large consumption of O_2 and production of CO_2 can be detected [32].

Concerning the physiological aspects, respiration is generally defined as the release of CO_2. However, respiration should be understood as multifaceted phenomena encompassing multiple aspects of the oxidative metabolism of organic acids and sugars through many different pathways, leading to either O_2 consumption or CO_2 evolution.

The concentration of gases in the surroundings of the fruit is a result of many metabolic events occurring. A few processes to mention that consume O_2 during ripening are (1) the lipoxygenase activity in the breakdown of fatty acids, producing volatile aldehydes related to flavor and aroma development in mature fruit [33]; (2) the oxidative cleavage of carotenoids to produce volatile apocarotenoids related to aroma and flavor [34]; (3) the O_2 activation by the ethylene-forming enzyme 1-aminocyclopropane-1-carboxylic acid oxidase [35]; (4) the chlorophyll breakdown by the action of pheophorbide a oxygenase (PaO) [36,37]; and (5) the alternative oxidase (AOX) pathway relieving the over-reduction status of the electron transport chain in mitochondria [38].

In the development of tomato fruit, the photosynthetic system operates, and the carboxylation proceeds by means of two carboxylation enzymes: ribulose-1,5-biphosphate carboxylase/oxygenase (RubisCO) and phosphoenolpyruvate carboxylase (PEPC). The PEPC activity in green and red-turning fruit is much higher than the RubisCO activity, and the suggested role of PEPC has been to refix CO_2 from respiration metabolism and generate malate, which decreases the osmotic potential in the cell, maintaining the positive turgor pressure that drives cell enlargement during the fruit-growing phase [39]. Bravdo et al. determined separately the carboxylase and oxygenase activities of RubisCO and the carboxylase activity of PEPC in the pink stage [40]. They found that when changing from the green to the pink stage, the carboxylation activity of RubisCO and PEPC dropped by half, while the oxygenase activity of RubisCO doubled, the glycolate content more than doubled, and the evolution of CO_2 increased considerably as well as O_2 consumption. RubisCO can perform the C2 cycle for recovering the C-skeleton from glycolate back to the C3 cycle, consuming O_2 and releasing CO_2 in a light-dependent mechanism called photorespiration. This agrees with the increase in oxygen consumption in the ripening transition stages and the increase in carbon dioxide evolution, as we found for light-treated tomatoes.

PEPC has an important function during the green stage, because it can refix CO_2 from the very intense respiration when a fruit is increasing its cell number and size, in addition to contributing to malate accumulation. As both PEPC and RubisCO carboxylase activities dropped consistently from the green to pink stages, followed by an increase in CO_2 evolution and O_2 consumption, these authors suggest that significant photorespiration occurred, as evidenced by the rise in glycolate. However, they did not assess the tomato phases in a closed and controlled environment but under natural day/night cycles in a green house. Photorespiration promoted by the oxygenase activity of RubisCO in the presence of light seems to be a component of the ripening arsenal, as it could give rise to glycolate, a precursor of H_2O_2, generating a pool of reactive oxygen species (ROS) that may trigger the onset of ethylene accumulation and ripening [40]. Recently, ROS signaling was linked to the phosphorylation of mitogen-activated protein kinase 6 (MPK6) and a subsequent strengthening of ACS6 (an ACC synthase subtype) followed by a rapid induction of ethylene action in *Arabidopsis thaliana* seedling tissue. A study conducted with tomatoes starting from the early green stage until ripening reported that in the color transition from green to red, until the ripening stage, the levels of peroxidase and catalase activity were kept high [41]. Such enzymes play a role in controlling the oxidative burst taking place. The oxidative transition states inside the plastids are part of the ongoing changes toward ripening, as was already reported for pepper [42] and papaya fruit [43]. However, studies clarifying the upstream events to ethylene signaling in fruit ripening, including the role of ROS, are incipient. Notwithstanding, ethylene is a central player to the proper coordination of ripening in tomato fruit, as for mutants in which ethylene production is compromised (*rin*, *cnr*, and *nr*), ripening is delayed [44].

Ethylene formation showed a linear increase (zero-order reaction kinetics) with and without light (Figure 3). Light promoted increased ethylene formation, as the reaction constant was 28% higher compared with that in dark storage conditions (Table 1). A nonlinear ethylene rise was observed after 10 d and 15 d in light or dark storage conditions, respectively (Figure 3), which is a characteristic of climacteric fruit, including tomatoes [45].

The tomato fruit is considered to perform both autoinhibitory system 1 and autocatalytic system 2 for ethylene production [38]. In this study, the ethylene biosynthesis and release would fit system 1 until around the 9th day for light treatment and then shift to system 2 at the 10th day. This coincided with the moment of accentuated O_2 consumption by the fruit in the presence of light (Figure 1), concomitantly with a discrete increase in CO_2 production (Figure 2). Concerning the dark-treated fruit, O_2 consumption did not show a considerable change, while CO_2 production tended to decrease from the 12th day onward. These results suggest that darkness influenced respiration and the set-up of the ripening-related changes. Hence, the occurrence of the hallmark respiratory rise and ethylene burst varied for the tomato fruit (cv. Toscano) according to the light conditions.

3.2. Effect of Light on the Quality Attributes of Tomato Fruit

Weight loss, titratable acidity, the maturity index, hue, and color difference showed a time dependence either with or without lighting (Spearman's test), while the lycopene and chroma values depended upon time just with lighting. The parameters were fitted according to the Power Law model (Table 2).

Table 2. Parameters of the Power Law model for fitting some quality attributes during tomato ripening in the presence and absence of lighting, where k stands for the reaction constant, n the order of reaction and R^2 the coefficient of determination.

Compound	With Light			Without Light		
	k	**n**	**R^2**	**k**	**n**	**R^2**
Weight loss	1.1×10^{-2}	0	0.914	5.5×10^{-3}	1	0.747
Titratable acidity	2.5×10^{-5}	0	0.968	6.3×10^{-4}	1	0.962
Maturity index	8.1×10^{-5}	2	0.965	7.2×10^{-4}	1	0.960
Lycopene	6.9×10^{-2}	0	0.812			
Hue	1.4×10^{-1}	0	0.946	9.2×10^{-10}	4	0.970
Chroma	3.3×10^{-5}	2	0.944			
Color difference	1.9×10^{-1}	0	0.813	1.0×10^{-1}	0	0.753

Weight loss, titratable acidity, the maturity index, hue, and color difference can be used as parameters to assess the long-storage shelf life of organically grown tomatoes.

Weight loss incremented over time, with a maximum of 2.70% found for the light-stored tomatoes after 12 d, being modeled by a linear (zero-order) model and exponential (1st-order) model for light and dark storage, respectively (Figure 4). Higher weight loss was detected in the presence of LED illumination without any statistical difference, according to the Friedman test for t = 6 d and t = 12 d. Considerable weight loss in fresh fruit is associated with a loss of freshness. Considering that, in the experimental conditions, water loss was minimized by high humidity and a low temperature inside the desiccators, weight loss may be the result of carbon loss due to the oxidative ripening metabolism. At this point, some weight loss by transpiration cannot be excluded.

The evolution of other quality parameters, such as the titratable acidity, maturity index, lycopene content, hue, chroma, and color difference of the stored tomatoes, can be observed in Figures 5–10, respectively.

A slight decrease in titratable acidity (TA) was observed during tomato storage without any significant difference for t = 6 d and t = 12 d both in the presence and absence of light (Figure 5).

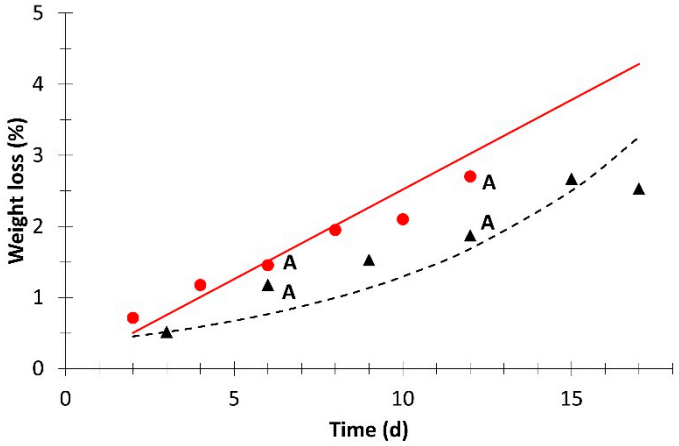

Figure 4. Weight loss during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –). Different letters for the same day indicate significant difference at $p \leq 0.05$.

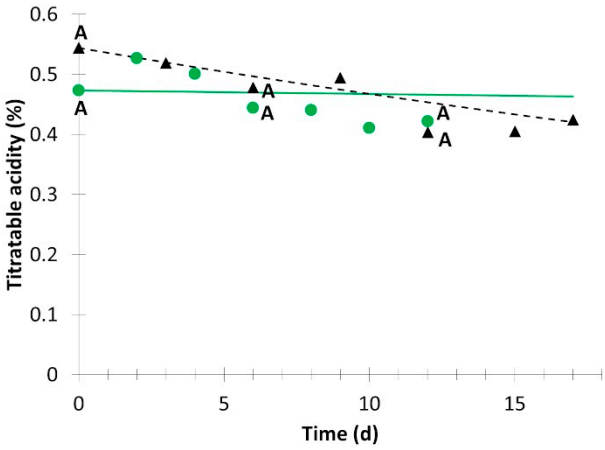

Figure 5. Titratable acidity during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –). Different letters for the same day indicate significant difference at $p \leq 0.05$.

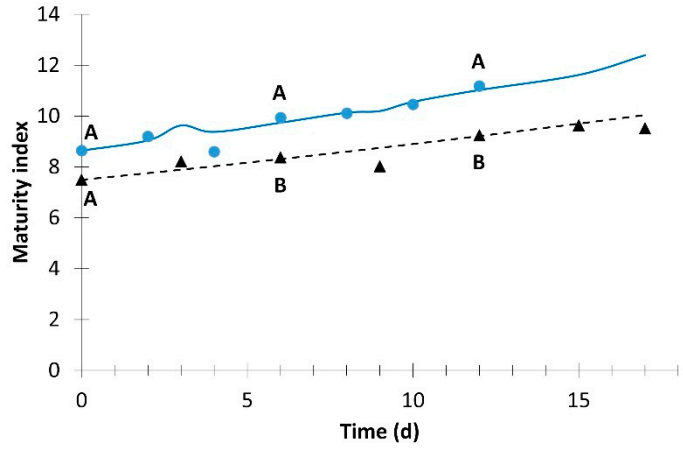

Figure 6. Maturity index during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –). Different letters for the same day indicate significant difference at $p \leq 0.05$.

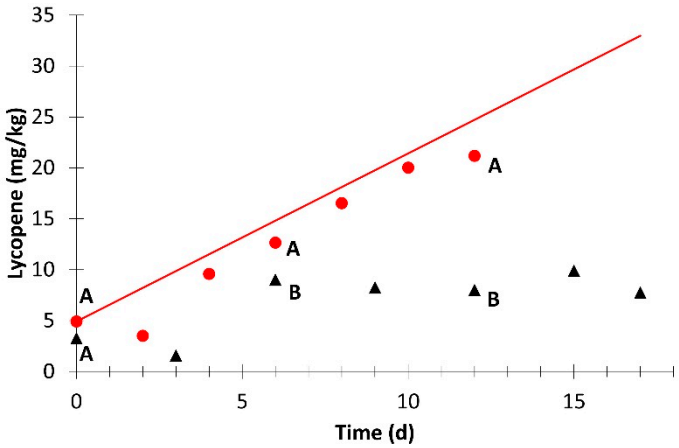

Figure 7. Lycopene content during ripening of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲). Different letters for the same day indicate significant difference at $p \leq 0.05$.

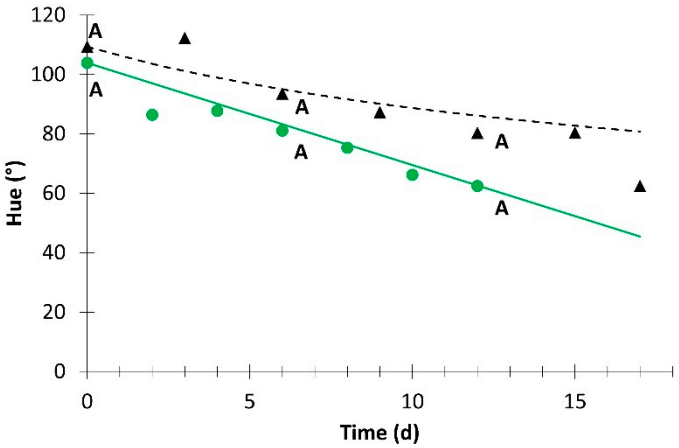

Figure 8. Hue of tomatoes during storage with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –). Different letters for the same day indicate significant difference at $p \leq 0.05$.

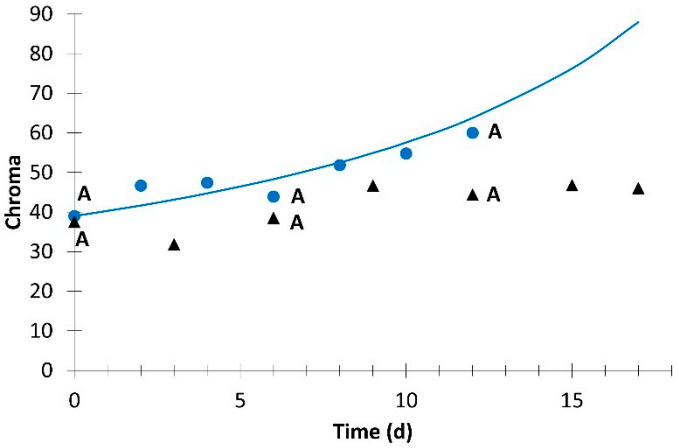

Figure 9. Chroma of tomatoes during storage with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲). Different letters for the same day indicate significant difference at $p \leq 0.05$.

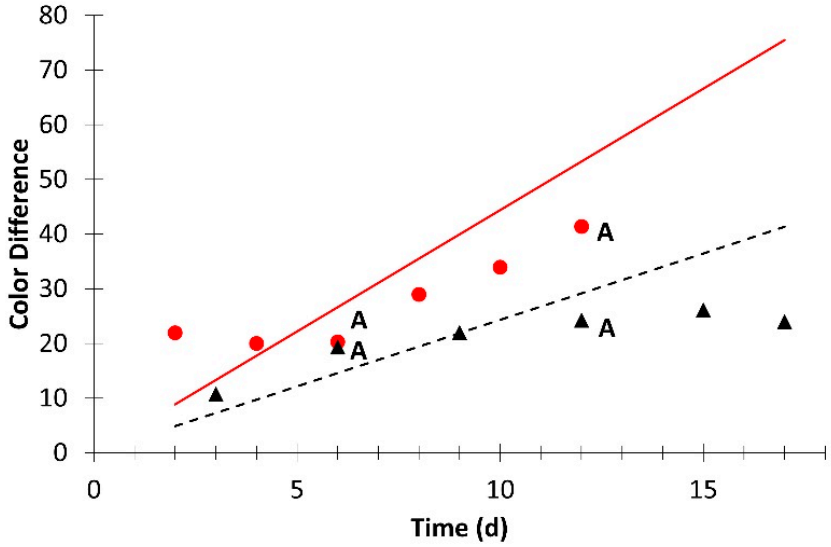

Figure 10. Color difference of tomatoes with light (experimental value: ●; simulation value: ——) and without light (experimental value: ▲; simulation value: – – –). Different letters for the same day indicate significant difference at $p \leq 0.05$.

A similar tendency was reported by Nájera et al. [46], who demonstrated a slight but significant effect of the red versus far red ratio of LED lamp exposure on the titratable acidity of tomatoes, while white light did not affect this parameter. The Power Law model fitting for TA suggests that the decrease in acidity is slower in tomato fruit stored in light conditions. The green area in a tomato is still photosynthesizing until the completion of ripening, as the transition of chloroplasts to chromoplasts does not occur synchronously [27,47]. It is plausible that the remaining photosynthesizing areas in the fruit tissues were still contributing to malate and other organic acid pools in the fruit. Nevertheless, this contribution will be low, as the reaction order changed only by one degree according to the Power Law model, as depicted in Figure 5. Organic acids such as malate decrease at the onset of ripening, leading to soluble sugar accumulation. Changes in the activity and amount of phosphoenolpyruvate carboxykinase (PEPCK) at different stages of fruit ripening were studied by Bahrami et al. [48]. They reported that PEPCK activity, which is related to malate dissimilation, was not detectable in either immature or mature pericarps in green fruits but was at the onset of fruit color changes at the breaker stage, with the maximum being in orange ripening fruit.

The maturity index demonstrated a continuous rise over time (Figure 6), affected mainly by the total soluble solids. This was the most suitable quality parameter for assessing the postharvest performance of tomatoes, due to its increase and significant difference for t = 6 d and t = 12 d for both dark and light storage conditions (Figure 6). The total soluble solids (TSS) in ripened fruit relates to the accumulation of photosynthesis assimilates such as starch in plastids during the green stages, when mitotic division defines the total cell amount in a fruit. The starch content increases to a maximum until the fruit reaches physiological maturity, and the level of soluble solids in a ripe tomato is related to the starch level in immature and mature green fruit [49,50].

Light exposure for tomatoes promoted the synthesis of lycopene, finally yielding 21.2 mg/kg of fruit (Figure 7), which is in the range of 18.6–65.0 mg/kg of fruit reported by Navarro-González and Periago [51]. Furthermore, the lycopene content without lighting increased from 3.3 mg/kg to about 8.6 mg/kg during the first six days and remained almost constant during further tomato ripening (Figure 7). LED light exposure for 12 h per day was able to increase the lycopene content by 150%. Nájera et al. reported an increase in lycopene between 30% and 60% for the tomato fruit subjected to LED light for 1 h per day [46]. At the breaker stage, the plastids begin to degrade chlorophyll, with the rate of lycopene formation being three- to fourfold higher than the rate of chlorophyll degrada-

tion [47]. In this stage, the respiration of starch provides energy and a carbon skeleton for secondary metabolism, such as carotenoid biosynthesis. Lycopene accumulation may occur independent of ethylene production by light transduction signals in fruit-localized phytochromes, although phytochromes and light stimulus have failed to induce ethylene production [52]. In our study, lycopene ceased to increase from the sixth day in the absence of light (Figure 7), despite ethylene being accumulated until the end of the experiment, in agreement with Alba et al. [52]. No statistically significant correlation was detected according to Spearman's test, which impaired the simulation.

The treatment that involved LED light exposure resulted in a more pronounced linear decrease in the hue angle compared with dark storage, although the data did not show a significant difference at t = 6 d and t = 12 d (Figure 8). However, previous results using similar experimental conditions, except for the application of continuous lighting for 9 days for traditionally cultivated greenhouse tomatoes (cv. Medano), indicated a statistically significant effect on the hue between the control and photolysis treatments [53].

Both UV-C and LED light affected the redness, yellowness, lightness, and color ratio (a*/b*) [7,46]. The development of color is related to chlorophyll degradation, a process promoted by chlorophyllase and the biosynthesis of orange and red carotenoids. The molecular mechanism regarding pigment biosynthesis control is complex because it involves the perception of light quality by phytochromes and cryptochromes, as well as the activation of a cascade of signaling and transcription factor-mediated gene expression control [54]. The circadian rhythm may also be related to pigment and other metabolite profiling, as the period of the day in which exposure to light happens will influence the content of the final metabolites [55].

The chroma or purity values increased slightly during tomato ripening in the presence of light (Figure 9). A previous study showed that tomato fruit chroma varied from 32.5 to 44.1 at different ripening stages on vine, with several pigment systems that conditioned the pigment types and quantity [4]. No statistically significant correlation was detected for chroma values without light, which impaired the simulation of this parameter.

The tomatoes stored with lighting showed a linear rise (0 order model) in color difference after t = 6 d, while this parameter reached a plateau value for dark storage conditions (Figure 10). A similar behavior was observed for the lycopene content (Figure 7).

According to our results, the tomato fruit were highly sensitive to lighting, as the quality parameter response was influenced by LED light, while the dark storage condition was able to delay ripening of the tomatoes. Finally, it is important to keep in mind that with the advances in tomato genetic breeding programs, hybrid or transgenic varieties may render new genotypes exhibiting different performance in the quality parameters related to ripening and LED light effects.

4. Conclusions

This study showed that artificial light affects the ripening and quality of organically grown tomatoes harvested at the breaker stage and stored at a low temperature and high humidity. Lighting was not able to delay ethylene production and respiration activity; on the contrary, it accelerated the pre-climacteric phase in comparison with dark-stored fruit. LED light also promoted lycopene formation and maturity index development after 6 and 15 days of storage. The Power Law model was able to fit the tomato quality attributes, such as weight loss, titratable acidity, maturity index, lycopene content, hue, chroma, and color difference, by using the zero, first, second and fourth orders of reaction. Power Law modeling for tomato fruit climacteric moment prediction proved to be reliable to study the dependence of ripening during storage on the presence of light or its absence. The ability to predict the pre-climacteric to climacteric phase transition is the basis for modern understanding of climacteric ripening. Special attention should be paid during storage of fresh tomato fruit in supermarkets, since light may accelerate ripening, decreasing their shelf life.

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