

Article

Supplemental LED Increases Tomato Yield in mediterranean Semi-Closed Greenhouse

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Abstract: Supplemental light (SL) is a technique used to increase horticulture yield, especially in northern countries, where the Daily Light Integral (DLI) is a limiting factor during fall and winter, and which could also be used to obtain higher tomato yield at the mediterranean latitude. In this study, three tomato hybrid (F1) cultivars were grown for year-round production in a commercial semi-closed glasshouse in Southern Italy: two of the cherry fruit-type ('Juanita' and 'Sorentyno') and one mini plum fruit-type ('Solarino'). From 120 to 243 days after transplant, light-emitting diode (LED) toplights were used as SL, with a photoperiod of 18 h. The main climatic parameters inside and outside the glasshouse were recorded, and tomato plants' development and yield were examined. Plants grown with LEDs had longer stems as compared to control treatment (9.53 vs. 8.79 m), a higher stem thickness and yielded more trusses. On average, the yield was 21.7% higher with LEDs. 'Sorentyno' was the cultivar with the highest cumulated productivity when it was grown under SL. However, the cultivar with best light use efficiency under LEDs was 'Solarino'. Therefore, supplemental LED from mid-December until March enhanced tomato growth and yield, opening a favorable scenario for large-scale application of this technology also in the mediterranean area.

Keywords: DLI; year-round production; light use efficiency

1. Introduction

The tomato (*Solanum lycopersicum* L.) is one of the world's fresh and processed fruits, and is the second most important vegetable crop after the potato worldwide [1]. The tomato is grown as an annual crop worldwide with different light intensities, temperatures, greenhouse designs and equipment that determine yield differences throughout the various regions of the world [2]. It is expected that the regions with more light, such as the mediterranean area, have higher yields than regions with less light (such as the Netherlands), but the level of greenhouse technology is often the most important factor influencing tomato plant yield [2]. For example, the average yield for tomatoes in Italy is around 7.6 kg m⁻² (ISTAT—Italian Institute of Statistics), while in The Netherlands, it is 60 kg m⁻² [2].

Light is the main factor that limits the year-round production of tomatoes in greenhouses. In fact, in Southern Italy, it is common to have two cropping cycles in one year (fall–winter and spring–summer) [3], increasing cultivation costs and decreasing plant production periods in comparison with Northern Europe.

On average, in the mediterranean basin, the Daily Light Integral (DLI) is five times higher in winter and 60% higher on an annual basis than in the Netherlands [2]. To improve the DLI, obtaining higher tomato yields, SL (supplemental light) technologies are frequently utilized in the northern hemisphere [4]. During recent years, in northern greenhouse cultivation, the most widely installed

lamps were the high-pressure sodium type (HPS) [5] that have a broad light spectrum for plant growth, and extra heat energy is currently incorporated into these light bulbs [6]. The second characteristic is particularly suitable for fall–winter tomato greenhouse production in northern regions because daily temperature is lower than in mediterranean areas, and by switching on the HPS lamps, the grower provides both light and heat to the plants at the same time. HPS cannot be used in mediterranean greenhouse cultivation because the daily temperature is higher, and the height of greenhouses is lower than in northern regions. Recently, another SL (light-emitting diodes: LEDs) technology is being developed, which has higher efficiency than HPS lamps [7]. LEDs can produce high luminous flux with low radiant heat and maintain their light efficacy for years, while HPS lamps need to be replaced more frequently and consume a great deal of electrical power by generating alongside visible light [8]. moreover, while HPS technology emits a large range of the SL spectrum between the yellow–orange wavelength, with LEDs, it is possible to optimize the spectral quality for various plants and different physiological processes [9]. Consequently, recent studies have shown that for tomato plants, the best LED SL spectrum for increasing tomato production is red + blue (RB) [10], with about 90–95% of the total radiation on the red (R) wavelength and 5–10% on the blue wavelength (B) [11–13]. moreover, when giving a small percentage of green (G) light on the RB background, the SL penetration on plant canopy increases [14]. Finally, a SL intensity around 100–150 $\mu\text{mol m}^{-2} \text{s}^{-1}$ significantly improves photosynthesis, plant growth and tomato quality [15]. These characteristics make LEDs suitable as an SL technology for mediterranean region greenhouse cultivation, particularly during the winter period when the average DLI is a limiting factor to tomato production. However, tomato plant responses to SL quality and quantity are influenced by cultivars [16].

Ouzonis et al. [17] found different plant height, leaf number and leaf area of nine tomato genotypes grown under RB SL [17], and Wei et al. [18] found different stem diameter, stem length, leaf number and leaf width of two tomato cultivars grown under RBG SL. These studies were carried out in an experimental greenhouse and for a brief growing cycle, while Gunnlaugsson and Adalsteinsson [19] found the different yields of two tomato cultivars grown under SL during a year-round cycle. Little information is available in the literature about the use of SL LED for year-round tomato production in mediterranean conditions. The aim of this paper is: (i) to assess the effects of LEDs as SL on the growth and yield of year-round tomato production in a commercial semi-closed glasshouse located in a typical area of the mediterranean basin, (ii) to investigate the response of three tomato cultivars to LEDs SL and (iii) to demonstrate that natural light is a limiting factor for obtaining high yield also in mediterranean conditions during the fall–winter period.

2. Materials and Methods

2.1. Experimental Set-Up

The trial was carried out at the commercial farm “F.lli Lapietra” placed in monopoli (BA), Italy (40.9027253 N, 17.3277492 E), in an innovative semi-closed glasshouse with a cultivation height of 4.5 m, gutter height of 7 m and a maximum height of 8 m. The roof of the greenhouse is covered with glass, Albarino Low Haze 2AR (Saint-Gobain), with 96.5% of light transmission measured with the Normal (NEN 2675) method. Light treatments (LED and natural light) were separated into two separate compartments (8064 m² surface) inside the greenhouse, and both were considered as “locations” in order to avoid all possible negative interaction between them (i.e., shadowing, microclimate, pests and disease outbreaks). Crop management practices were the same for all treatments and were based on local practices.

2.2. Plant Materials and Growing Conditions

Three hybrid (F1) tomato (*Solanum lycopersicum* L.) cultivars were tested: two of the red cherry fruit-type with an average fruit weight of 10–15 g (‘Juanita’, De Ruiters Seeds and ‘Sorentyno’, Gautier), and one of the red mini plum fruit-type, with an average fruit weight of 8–12 g (‘Solarino’, Rijk Zwaan).

The seedlings were obtained from a commercial nursery, using rockwool cubes (Grodan, $10 \times 10 \times 6.5$ cm). The day of transplant, the plants had eight true leaves and a stem length of 35 cm. On the 23rd of August, the plants were transplanted in rockwool slabs (Grodan Vital, $100 \times 20 \times 7.5$ cm). Three plants were transplanted in each slab at 0.33 m, and stem density was $4.73 \text{ stems m}^{-2}$. The plants were trained vertically and topped 238 days after transplant (DAT). The nutrient solution (NS) was supplied by self-compensating drip emitters (Netafim), one per plant, with a flow rate of 3 L h^{-1} . Plants were arranged on polyurethane-coated metal gutters (P.Tre s.r.l.) (length 100 m, width 0.20 m, 0.15% sloped, with distances between gutters of 1.92 m). Periodic operations of binding, lateral stem and basal leaf pruning were carried out. According to cultivar behavior, truss pruning was performed. During the tomato plant growing cycle, greenhouse day temperatures ranged from $22.5 \pm 2.32 \text{ }^\circ\text{C}$, while night temperature were $17.7 \pm 2.21 \text{ }^\circ\text{C}$, the average 24 h relative humidity was $67\% \pm 0.05\%$ and the average CO_2 concentration during the day was $482 \pm 77.52 \text{ ppm}$. Environmental parameters were controlled and recorded with the Priva Office Direct System (Priva BV). Pollination was guaranteed by the introduction of bumblebees (*Bombus terrestris* L.) into the greenhouse. Furthermore, integrated control of the principal pests was achieved by using chromotropic traps to monitor them, following release of predatory insects, parasitosis and localized treatments with selective active agents on any plants showing symptoms of infestation.

During the cultivation, rainwater and underground water was used to prepare NS. Electrical conductivity (EC) was $<0.7 \text{ mS cm}^{-1}$, while Cl and Na concentrations were respectively 16.1 and 31.5 mg L^{-1} . For this reason, water quality was ranked as 1 [20]. moreover, underground water had 414.4 mg L^{-1} of bicarbonates, so before fertilizing, dilution water was automatically pre-acidified (Neutralizer, Priva BV) with nitric acid until reaching a pH of 5.8–6.0 and $35.5\text{--}48.8 \text{ mg L}^{-1}$ of bicarbonates. NS composition (expressed in $\text{mg}\cdot\text{L}^{-1}$) was adjusted during the growing cycle according to the plant stage: 134 N- NO_3 , 10 N- NH_4 , 161 K, 50 P, 25 mg, 124 Ca, 21 Cl and 33 S from transplanting until third truss flowering, 150 N- NO_3 , 18 N- NH_4 , 249 K, 39 P, 27 mg, 118 Ca, 26 Cl and 48 S from the third truss flowering to fifth truss flowering and 124 N- NO_3 , 5 N- NH_4 , 300 K, 41 P, 12 mg, 94 Ca, 19 Cl and 47 S from the fifth truss flowering to the end cycle. The micro-nutrient concentration was the same throughout the growing cycle, according to Hoagland and Arnon [21]. NS was re-circulated according to closed cycle management and it was never discharged during the growing cycle. Drainage NS was collected from each gutter in a tank and disinfected with a ultraviolet (UV) disinfection system (Priva Vialux m-Line, Priva BV). After that, the disinfected drainage NS was collected in another tank and integrated with the new NS by fertirrigator led by pH and EC values. The fertigation schedule was set to avoid plant water stress, so the number of irrigation events was continually changed during the plants' growth depending on the environmental conditions and the plant stage. Rockwool moisture was continually checked with the 'Priva moisture Balance module' (Priva BV.) connected to the 'Priva Office Direct'. The harvest started between October and November (depending on the cultivar).

2.3. Supplemental Light Treatment and Daily Light Integral (DLI) Measurements

The supplemental light (SL) technology used during this experiment was GreenPower LED Toplight version 1.2 Deep Red/White/Low Blue High Output (Signify). Fixtures were installed above each plant or under the gutter. The distance between LEDs and the plants head was 1.70 m and, considering this distance from the fixtures, the average photosynthetic photon flux density (PPFD) emitted from the LEDs was $168 \mu\text{mol m}^{-2} \text{ s}^{-1}$. SL treatment started 120 DAT and during the first week of the treatment, the photoperiod was increased one hour per day until reaching the photoperiod of 18 h. On 120 DAT 12 h of photoperiod was set, and from 126 DAT to the end of SL treatment, 18 h of photoperiod was set. To accomplish this, the LEDs were switched on eighteen hours before sunset. SL treatment was stopped 243 DAT, because the DLI of natural light in the glasshouse was above $25 \text{ mol m}^{-2} \text{ d}^{-1}$. To measure PPFD and DLI in the glasshouse, a quantum sensor (LI-191SA, LI-COR Biosciences) was placed at the height of the tomato plants' heads.

2.4. Yield and Plant Parameters Measurements

Seven DAT, six or eight plants per each cultivar were marked in both greenhouse compartments. All the measurements were made every seven days on these plants, until the end of the cycle. The parameters considered were stem elongation, stem diameter, leaf length, fruit per truss and trusses harvested. The length of the stems was measured by adding up the weekly growth of the stems, while the stem diameter was measured at 30 cm below the plant head. The leaf length was the length of the third leaf under the last flower with trusses considered. It was measured from the leaf insertion point on the stem up to the apical part of the apical leaflet. The fruit per truss was the average number of fruit per each truss on the plant at that moment. moreover, for each cultivar and for both natural light (NL) and LED treatments, the average of harvested fruit weight was determined weekly. Yield was calculated every week for each plant, with the following formula: $((\text{Average fruit weight}) \times (\text{Average fruit number per truss})) / (\text{Number of harvested trusses during the week})$.

2.5. Use of Electricity and Light Use Efficiency

The electrical power consumption of each fixture was 200 W. To calculate the electrical energy consumption per square meter, this formula was used: $[(\text{Total amount of fixtures}) \times (\text{Single fixture power consumption}) \times (\text{Total amount of hours of SL lighting})] / (\text{SL compartment surface})$.

The total number of fixtures was 2220 units, the total number of hours of SL lighting was 1347 h and the SL surface was 8064 m².

To calculate the electrical energy use efficiency, the formula described by Tewolde et al. [22] was used: $\text{Electric energy use efficiency (g kWh}^{-1}) = (\text{Yield increase with LED treatment (g m}^{-2}) / (\text{Electric energy consumption (kWh m}^{-2}))$.

Finally, to calculate Light Use Efficiency (LUE), the following formula was used: $\text{Light use efficiency (g mJ}^{-1}) = (\text{Electric use efficiency (g kWh}^{-1}) / (\text{The conversion coefficient from electrical energy to photosynthetically active radiation energy})$ [22]. LED modules used during this experiment had a conversion factor of 3.1 $\mu\text{mol J}^{-1}$.

2.6. Statistical Analysis

Data were collected on six plants per treatment (unless otherwise stated). All data were submitted to analysis of variance (ANOVA) and/or regression using the General Linear model and/or Regression procedures (GLM and RGR Proc; SAS Software, Cary, NC, USA). The experimental factors were fixed in a two-way analysis of variance (ANOVA). The least significant difference (LSD) test ($p = 0.05$) was used to establish differences between means.

3. Results

3.1. Daily Light Integral (DLI)

The DLI in the greenhouse decreased from the day of transplant (23 August) to 120 days after transplanting (DAT); on average, DLI was $21.89 \pm 6.4 \text{ mol m}^{-2} \text{ d}^{-1}$ between 1 and 30 DAT, $17.90 \pm 4.17 \text{ mol m}^{-2} \text{ d}^{-1}$ between 31 and 60 DAT, $13.77 \pm 4.35 \text{ mol m}^{-2} \text{ d}^{-1}$ between 61 and 90 DAT and $8.59 \pm 3.62 \text{ mol m}^{-2} \text{ d}^{-1}$ between 90 and 120 DAT (Figure 1). After 120 DAT, LED treatment started and the DLI of the two experimental compartments was different (Figure 1). The tomato plants grown in the LED compartment received more DLI than those grown in the NL compartment: 93% (19.73 vs. 10.21 $\text{mol m}^{-2} \text{ d}^{-1}$), 61% (23.60 vs. 14.69 $\text{mol m}^{-2} \text{ d}^{-1}$), 32% (27.20 vs. 20.63 $\text{mol m}^{-2} \text{ d}^{-1}$) and 9% (30.16 vs. 27.70 $\text{mol m}^{-2} \text{ d}^{-1}$), between 121 and 150, 151 and 180, 181 and 210, and 211 and 243 DAT, respectively. After 243 DAT, the LEDs were switched off definitively and the average DLI was $27.25 \pm 7.02 \text{ mol m}^{-2} \text{ d}^{-1}$ (Figure 1).

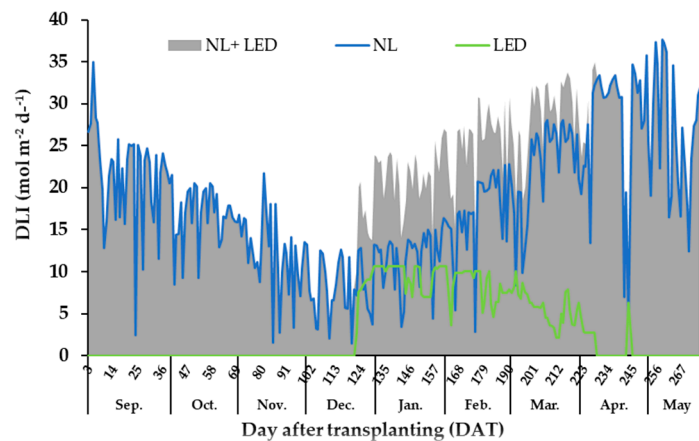


Figure 1. Daily light integral (DLI) measured in the greenhouse during the tomato plant growing cycle. Natural light (NL) + light-emitting diode (LED) is the sum of the DLI obtained from sunlight and LED, NL is the DLI obtained from sunlight, while LED is the DLI obtained from the supplemental light fixtures.

3.2. Plant Growth and Yield

At the end of the growing cycle, tomato plants grown under LEDs differentiated four more trusses (12.5% more) compared with the plants cultivated without supplemental light (SL, Table 1). On average, ‘Juanita’ and ‘Solarino’ differentiated two additional trusses (6% more) than ‘Sorentyno’ (Table 1). The highest number of harvested trusses was obtained by ‘Solarino’, which was grown with SL (Figure 2). It had 18% more trusses harvested than the same cultivar grown without SL and showed 6% and 18% more trusses harvested than ‘Juanita’ and ‘Sorentyno’ respectively, which were cultivated under the same light conditions (Figure 2). ‘Juanita’, cultivated under LEDs, showed 21% more trusses harvested than under NL (Figure 2). moreover, comparing the two tomato cherry-type cultivars, ‘Juanita’ under LED showed respectively 6% and 19% more trusses harvested than ‘Sorentyno’ cultivated under and without SL (Figure 2). Finally, when ‘Sorentyno’ was grown under LEDs, it had 11% more trusses harvested than plants grown under NL (Figure 2).

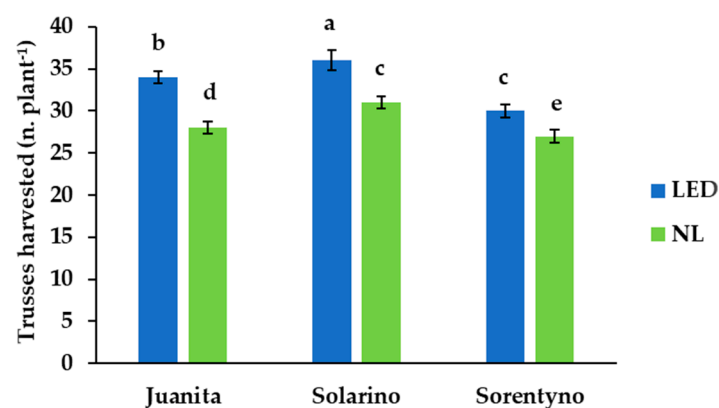


Figure 2. Number of the trusses harvested at the end of the growing cycle of three tomato cultivars grown with LEDs, used as supplemental light, and with natural light. Vertical bars indicate \pm standard error (SE). The same lowercase letters indicate that the mean values are not significantly different ($p = 0.05$).

Table 1. Effects of supplemental light (SL) treatment (LEDs) and cultivar on flower truss, harvest truss, stem length, stem diameter, leaf length, fruit per truss and yield of tomato plants. LEDs were switched on from 122 to 243 days after transplanting (DAT). Values in the table are the average of measurements taken during the growing cycle.

	Flower Truss	Harvest Truss	Stem Length	Leaf Length	Fruit Per Truss	Yield
	n.		cm	cm	n.	g plant ⁻¹
Light (L)						
LED	36	33	953	34.52	12.94	4572
Natural Light	32	29	879	35.12	13.46	3757
Cultivar (CV)						
Juanita	35 a	31 b	927 a	32.45 c	15.17 a	4609 a
Solarino	35 a	33 a	918 ab	35.14 b	13.20 b	4220 b
Sorentyno	33 b	29 c	898 b	37.66 a	10.56 c	3517 c
Significance ⁽¹⁾						
L	***	***	***	NS	NS	***
CV	***	***	*	***	***	***
L × V	NS	**	**	NS	**	NS

⁽¹⁾ Significance: ***, ** and * respectively for $p \leq 0.001$, $p \leq 0.01$ and $p \leq 0.05$; NS, not significant. Within the same main effect and for each parameter, the same lowercase letters in the same column indicate that the mean values are not significantly different ($p = 0.05$).

‘Juanita’ and ‘Solarino’ grown under LEDs showed the longest stem length: about 6% longer than ‘Sorentyno’, which was grown with LEDs (Figure 3). moreover, with LEDs, the stems were longer than plants grown without LEDs: ‘Juanita’, ‘Sorentyno’ and ‘Solarino’ had stems that were respectively, 8%, 13% and 14% longer (Figure 3).

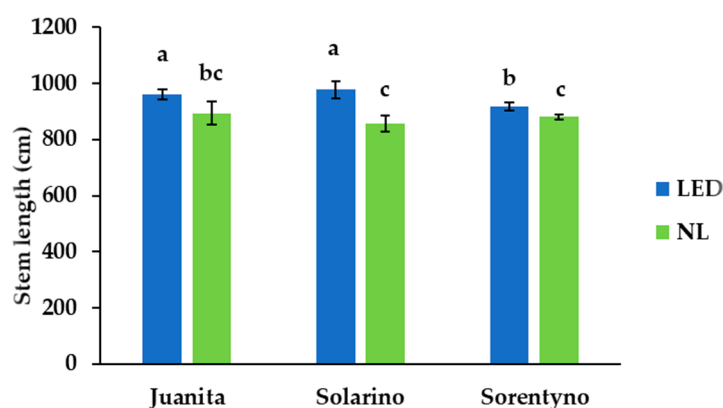


Figure 3. Stem length at the end of the growing cycle of three tomato cultivars grown with LED, used as supplemental light, and with natural light. Vertical bars indicate \pm SE. The same lowercase letters indicate that the mean values are not significantly different ($p = 0.05$).

No difference was found in leaf length between the two different light conditions, but ‘Sorentyno’ showed leaf length that was 7% higher than ‘Solarino’ and 16% higher than ‘Juanita’ (Table 1). At the same time, when no LEDs were used, ‘Juanita’ showed, on average, the most fruit per truss (Figure 4): 12% higher than plants grown under LEDs. For ‘Solarino’ and ‘Sorentyno’, no difference was found when comparing light treatments (Figure 4). moreover, ‘Juanita’ had 15% more fruit per truss than ‘Solarino’ and 44% more than ‘Sorentyno’ (Table 1). Finally, ‘Solarino’ had 25% more fruit per truss than ‘Sorentyno’ (Table 1).

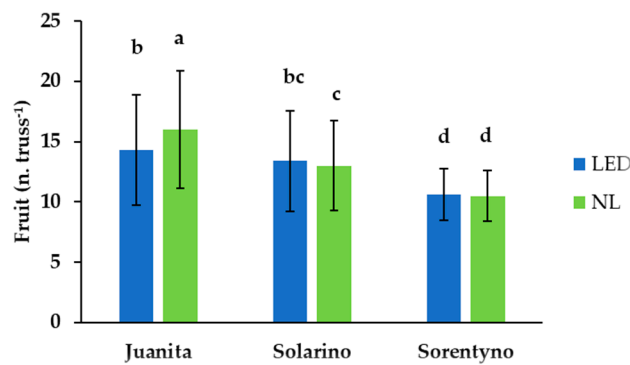


Figure 4. Average number of fruit per truss during growing cycle of three tomato cultivars grown with LED, used as supplemental light, and with natural light. Vertical bars indicate \pm SE. The same lowercase letters indicate that the mean values are not significantly different ($p = 0.05$).

On average, stem diameter was 8% more for tomato plants grown under LEDs than without SL, but different trends over time were found (Figure 5A–C). The regression curves found to describe stem diameter growth under LEDs and without LEDs during the growing cycle were parallel for ‘Solarino’ plants (Figure 5A), while they showed fewer differences for ‘Sorentyno’ (Figure 5B) and more for ‘Juanita’ (Figure 5C).

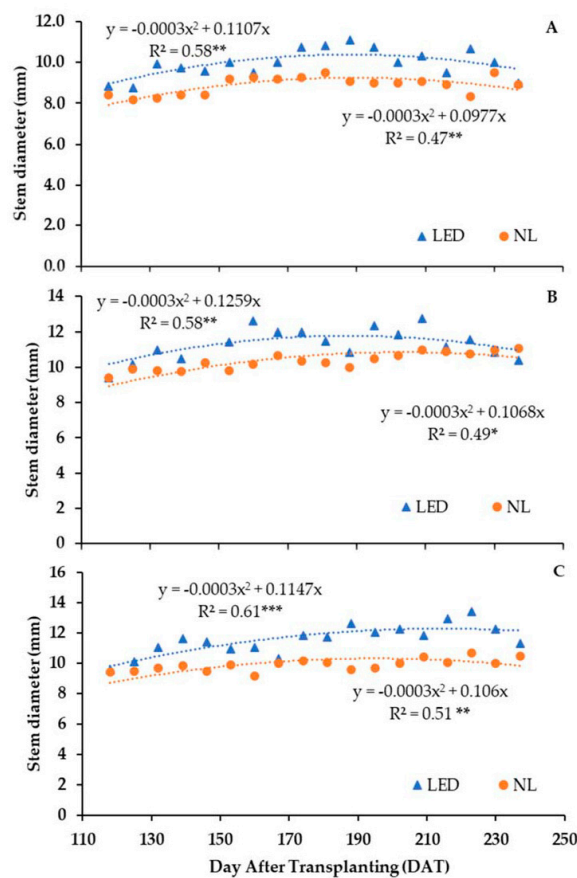


Figure 5. Relationship between stem diameter and day after transplant (DAT). Each symbol represents the mean of six replications for ‘Solarino’ (A) and ‘Sorentyno’ (B) and of eight replications for ‘Juanita’ (C). Different symbols and colors represent the different light treatments. Regression equations and R² coefficients are presented. ***, ** and * indicate significance at $p \leq 0.001$, 0.01 and 0.05, respectively.

Fruit weight increased over time (from 5.9 to 16.0 g) but with different trends for the three cultivars, and in relation to whether LEDs were used or not (Figure 6A–C): it reached 16.0 g in ‘Sorentyno’ and 12.6 g, on average, in ‘Solarino’ and ‘Juanita’, with minor differences at the beginning and at the end of LED application.

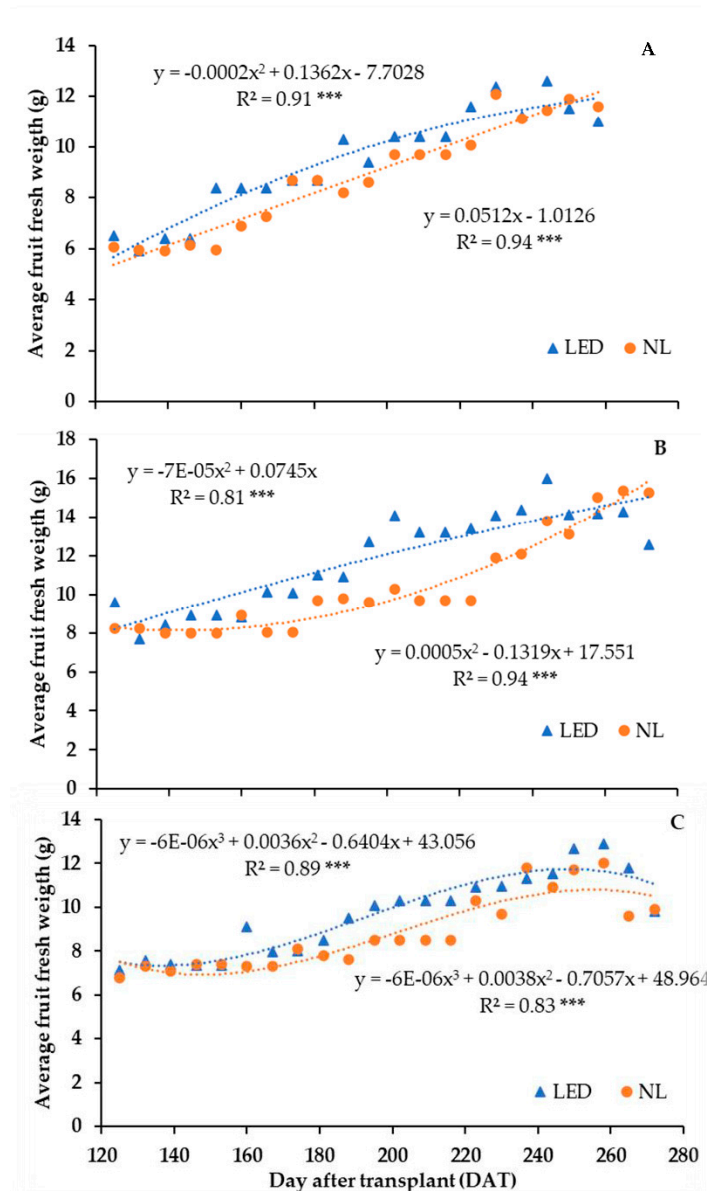


Figure 6. Relationship between average fresh fruit weight and days after transplant (DAT). Each symbol represents the mean of six replications for ‘Solarino’ (A) and ‘Sorentyno’ (B) and of eight replications for ‘Juanita’ (C). Different symbols and colors represent different light treatments. Regression equations and R² coefficients are presented. *** indicates significance at $p \leq 0.001$.

Tomato plants grown under LEDs produced 815 g plant⁻¹ (21.7%) more than those grown with only NL (Table 1). ‘Juanita’ was the cultivar with the highest yield: 9% and 31% higher than ‘Solarino’ and ‘Sorentyno’, respectively (Table 1). From beginning of harvest until the beginning of SL treatment (120 DAT), no differences were observed in the two compartments in any of the three cultivars (Figure 7C). During the SL treatment (between 121 and 243 DAT), ‘Juanita’ grown under LEDs produced 24% more as compared to control treatment (9.4 vs. 7.5 kg m⁻²), while from 243 DAT (the day that LEDs were switched off) until the last harvesting, any differences between the

greenhouse compartments were found and the average yield was 9.6 kg m^{-2} (Figure 7C). Similarly, during SL treatment, ‘Solarino’ grown under LEDs showed about 58% more yield than the same cultivar grown without LEDs ($8.2 \text{ vs. } 5.5 \text{ kg m}^{-2}$), while from 244 DAT to the last harvest, ‘Solarino’ grown in the LED compartment produced about 36% more as compared to the NL compartment ($8.7 \text{ vs. } 6.4 \text{ kg m}^{-2}$ —Figure 7A). When SL was switched on, ‘Sorentyno’ produced 7.3 kg m^{-2} under LED and 5.1 kg m^{-2} without LEDs (Figure 7B), while during the last period ‘Sorentino’ in the LED compartment showed 18% more yield than in the NL compartment ($6.7 \text{ vs. } 5.7 \text{ kg m}^{-2}$ —Figure 7B).

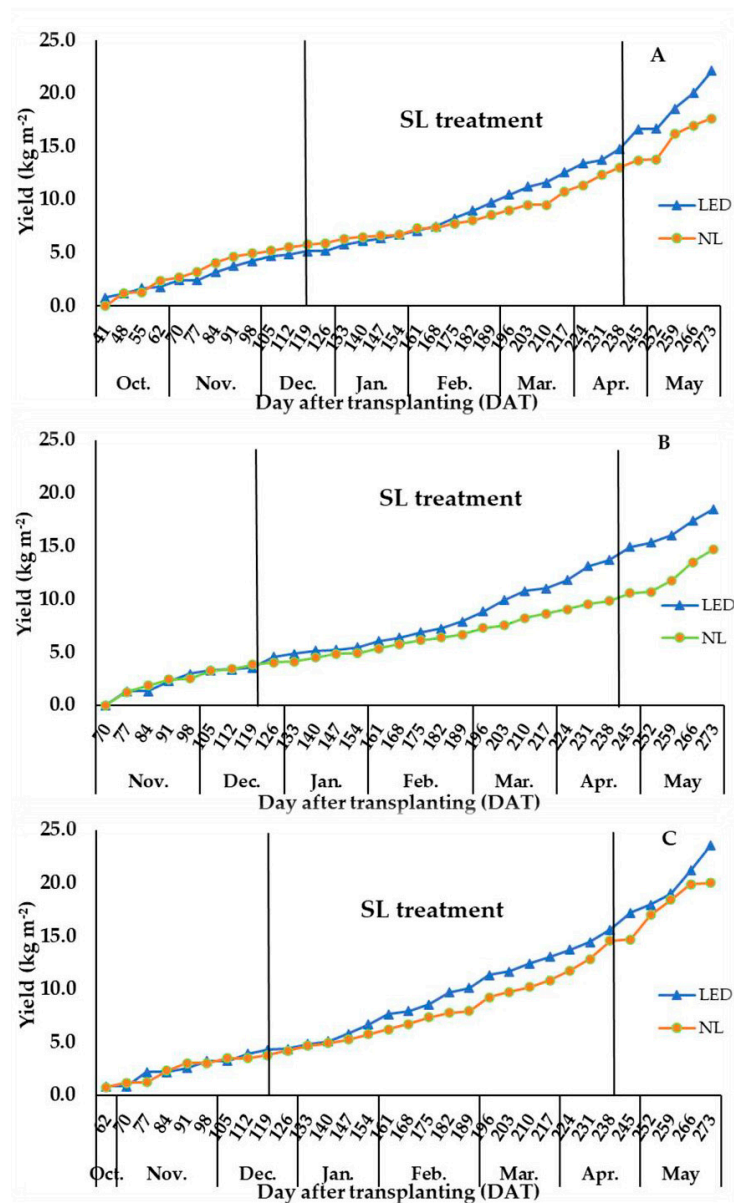


Figure 7. Cumulative trends of yield during the harvests. LEDs for SL treatment were switched on between 122 and 223 DAT. Each symbol represents the mean of six replications for ‘Solarino’ (A) and ‘Sorentyno’ (B) and of eight replications for ‘Juanita’ (C). Different symbols and colors represent different light treatments.

4. Discussion

4.1. Daily Light Integral (DLI)

DLI of 13.0–17.3 mol m⁻² d⁻¹ is essential for young tomato plant growth, while for adult tomato plants cultivated in the growth chamber, the DLI reached 30–40 mol m⁻² d⁻¹ [23]. For greenhouse conditions, the reduction in tomato yield due to 1% less radiation varied between 0.6% and 1.1%, depending on the cultivar [24]. moreover, in commercial greenhouses, a DLI of 22–25 mol m⁻² d⁻¹ is optimal for tomato year-round production [25]. The “optimal” DLI can also depend on specific cultivar yield characteristics, produce market prices, costs of electricity, heating fuel and light fixtures, installation and maintenance costs, interest costs on capital, and fertilizer, water, labor and even CO₂ costs [26]. In the mediterranean area, the use of SL technology in greenhouses has not yet been developed, because it is believed that there is enough natural light (NL) for tomato plant growth. During the late spring and summer period, NL is high (also >30 mol m⁻² d⁻¹) and the tomato growers generally use a shadow screen to reduce DLI and temperature in the greenhouse. For this reason, until now, the general thought of the tomato growers in the mediterranean area is that SL investment for year-round cultivation of tomato plants is not necessary in order to increase yield. In fact, there are few farmers that invest in this technology at this latitude.

During this study, we demonstrated that this may not be the case due to the fact that the recorded results from the end of September until the end of march were such that the natural DLI in the greenhouse was always lower than optimal (Figure 1). From the end of September until December, the natural DLI continually decreased. Therefore, in order to avoid a decrease in yield in this area, SL technology is needed from the end of September. Unfortunately, we only began SL treatment from 21 December (Figure 1) because we operated in a new commercial greenhouse where LED installation was completed in December. Thus, the tomato yield obtained in our experiment would probably have been even greater if the SL treatment had begun in September. However, during the period that SL was switched on, the DLI under LEDs was in the optimal range for tomato crops [23,25], while the plants grown under NL had less light compared to optimal conditions (Figure 1). The DLI obtained under LEDs was a great result when compared with Northern European countries, such as Norway (58°42′49.2″ N 5°31′51.0″ E), where from October to February, the natural DLI in the greenhouse is always under 10 mol m⁻² d⁻¹ and it never reaches 25 mol m⁻² d⁻¹ with LED SL [27]. In detail, considering a tomato cycle from September to march, the total light integral (TLI) of natural light in the greenhouse in Norwegian conditions is around 1040 mol m⁻² [25], while at the latitude in our study, TLI was almost 3 times higher (Figure 1). With SL application, TLI in Norwegian greenhouses increases to 5640 mol m⁻² for the same cultivation period [25], and for this reason, tomato yield is higher in Norway than in Italy. So, in the mediterranean area, NL could be a limiting factor for year-round tomato production, and tomato plants grown in Northern countries with SL receive more light than those cultivated in the mediterranean basin without SL. During our experiment, switching on LEDs from mid-December until the end of march, we obtained a TLI of 5662 mol m⁻² (Figure 1). This means that if we had started with SL application from the end of September, we would have had more light than in Norway, increasing our fruit yield.

4.2. Plant Growth Yield and Light Efficiency

As described previously, from transplant to 120 DAT, tomato plants were cultivated without LEDs (Figure 1) and any difference was recorded by comparing the two experimental compartments considering plant growth and yield (Figures 5–7). Before SL treatment, preliminary measurements were made to evaluate photosynthesis activity and plant gas exchange systems (data not shown). On average, the net photosynthesis activity (*A*) was 14.0 ± 2.3 μmol CO₂ m⁻² s⁻¹, transpiration rate (*E*) was 10.1 ± 1.2 mmol H₂O m⁻² s⁻¹ and stomatal conductance (*g_s*) was 0.407 ± 0.115 mol H₂O m⁻² s⁻¹. When the SL treatment started, the differences in terms of growth and yield between plants grown with LEDs and those grown with NL became more and more relevant and often cultivar-specific

(Figures 5–7). However, leaf length varied between the cultivars, but not between light conditions (Table 1). During SL treatment, the tomato crop under LEDs developed more rapidly than under NL, so more flowering trusses were differentiated (Table 1). While the number of flowering trusses increased for each genotype, when plants were grown with SL, the same effect was not observed on the number of fruit per trusses (Table 1). In fact, irradiance positively influences the number of flowers per each inflorescence, but at same time, this characteristic is strictly linked to genotype [28]. When ‘Juanita’ was grown under LEDs, it showed less fruit per truss than under NL (Figure 4). This result was not surprising, because when this cultivar was grown under NL, during the winter period, generally it promoted the inflorescence branching, while during the spring–summer period, this was not usual. Heuvelink and Okello [28] report that low air temperature during inflorescence initiation promotes inflorescence branching and, in particular, it is the mean diurnal temperature that controls branching and fruit number. During our experiment, ‘Juanita’, grown with SL, had only single inflorescence, while under NL, it often showed the inflorescence with double branching, with more fruit per truss than under LEDs (Figure 4). With SL, the photoperiod during wintertime increased up to 18 h, so the night was only 6 h long. Therefore, the 24 h average temperature was higher under LED than under NL, and for ‘Juanita’, the differentiation of branched inflorescence was inhibited. ‘Solarino’ differentiated branched inflorescence but, in contrast to ‘Juanita’, had branched inflorescence under both light conditions, while ‘Sorentyno’ under whatever light condition differentiated only single inflorescence, and also for this cultivar, no difference in number of fruit per truss between light conditions was found (Figure 4).

When tomato plants were grown under SL, stem height and diameter increased (Table 1 and Figure 5). Regarding these parameters, different trends were found in previous studies. Some authors found that by increasing light intensity and DLI, plant height decreased and stem diameter increased [29–31], while for other authors, SL did not influence stem length and diameter [32]. Trends are often contradictory because stem growth is strictly influenced by other environmental factors, such as temperature and relative humidity [28], and, as we found during our experiment, it is cultivar-dependent (Figures 3 and 5). On average, ‘Juanita’, ‘Solarino’ and ‘Sorentyno’ grown under NL had the same stem length, while under LEDs, ‘Sorentyno’ showed a shorter stem length than ‘Juanita’ and ‘Sorentyno’ (Figure 3). Probably, in order to increase the stem elongation of ‘Sorentyno’, a higher day temperature was needed, compared to the other cultivars [28]. Generally, from the transplant until mid-December, the stem diameter decreased, or its growth curve was almost flat, while from the day that SL was switched on until the end of the cycle, stem diameter increased (Figure 5). These trends could be explained with a positive correlation between light intensity and increase of stem diameter because the increase in photosynthetic assimilates contributes to stem diameter growth [33]. However, the trend of stem diameter growth was cultivar-dependent and well represented by the equations of regression curves (Figure 5).

Tomato yield was not influenced by the number of fruit per truss, as described before, but the average fruit weight played a fundamental role in it (Figure 6). Considering this parameter, generally, plants grown with SL showed higher values than under NL (Figure 6). The same results were obtained from Paucek et al. [34] with supplemental LED inter-lighting. Like most growth processes, fruit development is dependent on temperature [28], and, at same time, tomato fruit are capable of photosynthesis and may contribute up to 20% to the fruit photosynthate content [34]. So, they could use the light from SL to increase carbohydrate synthesis and average fresh fruit weight. moreover, a lot of genes are involved in fruit development [28], so the average fruit weight is influenced by environmental and genetic factors. In Figure 6, it is possible to observe that from 160 to 240 DAT, the average fruit weight was often higher for the plants grown under LEDs than without LEDs, while in the beginning and at the end of the crop cycle, the fruit weight was almost the same. In fact, from 160 to 240 DAT, the fruit developed completely under LEDs had more photosynthesis activity. Also, in this case, as for stem diameter, the regression equations described the average fruit weight development for each cultivar under SL and NL conditions with a highly significant R^2 (Figure 6).

Generally, after the beginning of SL treatment, plants under LEDs grew more rapidly than those without SL. For this reason, the plants grown under LEDs had longer stems, more flowering trusses, more trusses that were harvested and higher average fruit weight than under NL (Table 1, Figure 2). In particular, the average fruit weight and the ripening speed influenced yield (Figure 7). Before the SL treatment started, the plants that were grown in the two compartments showed the same yield, while from the beginning of light treatment until the end of the cycle, the plants grown under LEDs had a higher yield than those without SL (Figure 7). On average, the yield obtained with LEDs was 21.6 kg m^{-2} , which was lower by about 25.0 kg m^{-2} as compared to that obtained by Dueck et al. [35] during an experiment conducted in the Netherlands with the same growing cycle and tomato typology as our experiment. If we consider that we started late with SL application, the average yield obtained during our experiment under SL was comparable with the yield obtained in the Netherlands. Considering cumulate total yield (Figure 7), the differences between light treatments started about 60 days after the first day of SL application, and, on average, at the end of the cycle, the tomato yield was 22% higher under LEDs than without SL (Figure 7). During a similar experiment conducted in Bologna (Italy, $44^{\circ}34'49'' \text{ N}$, $11^{\circ}31'54'' \text{ E}$) from January to September with a beef tomato cultivar, plants grown with LEDs showed 16% more yield than plants grown with NL [34]. Probably, the differences between LEDs and control treatments was higher for our experiment, because the average external cumulated solar radiation was on average $1900 \text{ J cm}^{-2} \text{ d}^{-1}$ for Paucek et al. [34], while during our experiment it was $1118 \text{ J cm}^{-2} \text{ d}^{-1}$ (data not shown). So, during our experiment, the plants grown only with NL had less light available than during the experiment of Paucek et al. [34]. Considering yield, 'Sorentino' was the cultivar with the highest difference between SL and NL conditions, because, as described previously, this cultivar did not differentiate branched inflorescence under NL, while, instead, this occurred for 'Juanita' and 'Solarino' with the reduced advantage of LED application (Figure 7). However, 'Juanita' was the cultivar with the highest yield for the cultivars used during this experiment (Figure 7).

But, how much of an increase in energy costs does this produce? The total electric energy used was 75 kWh m^{-2} ; so, the electric energy use efficiency, expressed as g kWh^{-1} , was 47.6, 57.5 and 50.5 for 'Juanita', 'Solarino' and 'Sorentino', respectively. This means that 'Solarino' was the cultivar that used LED SL more efficiently than the other two cultivars. In fact, LUE for 'Solarino' grown under LEDs was 18.6 g MJ^{-1} , while for 'Sorentino' under SL, it was 16.3 g MJ^{-1} , and for 'Juanita' it was 15.3 g MJ^{-1} . These results confirm the sum of day and night LUE of 16.3 g MJ^{-1} obtained by Tewolde et al. [22].

5. Conclusions

In the mediterranean basin, during a fall–winter tomato cultivation, the amount of natural light is a limiting factor to obtaining high yield. During this experiment, it was demonstrated that by using LEDs as supplemental light, from mid-December to the end of march, crop growth and yield increased consistently. moreover, an interaction was found between supplemental light and tomato varieties. Indeed, 'Solarino' used supplemental light more efficiently than the other two cultivars. Further studies will be necessary to understand the effects of SL applications on fruit quality and on the photosynthesis of tomato plants as well as determine what the increase in yield may be if the SL application starts from the end of September to guarantee an optimal DLI during the whole crop cycle. Finally, an economic analysis needs to be developed in order to understand if SL investment would be economically sustainable for mediterranean growers.

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