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Proposed Light Wavelengths during Healing of Grafted Tomato Seedlings Enhance Their Adaptation to Transplant Shock

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Abstract: Tomato, which is mainly established with grafted seedlings, is one of the most popular vegetables worldwide with a high nutritional value,. Market demand for grafted seedlings is high in specific seasons; thus, commercial nurseries face a problem of limited space availability during the healing stage. Light quality is an essential parameter during healing that can adjust seedling development towards desirable traits and lead to time and space saving during seedling production. Moreover, transplant shock constitutes another challenge that could limit crop yield. The objective of this study was to evaluate the overall quality of grafted tomato seedlings and their potential adjustment to transplant shock as affected by different light spectra during healing in a chamber. Evaluations were conducted immediately after exiting the healing chamber and after transplantation into pots. Light wavelengths were used from fluorescent lamps (FL) or light-emitting diodes with red (R), blue (B), red–blue combinations with 12 and 24% blue (12B and 24B), and white (W) emitting 11% blue. W enhanced the dry shoot biomass and the root architecture before and after transplantation. 24B led to an increased stem diameter, root development, and phenolic and antioxidant accumulation at both phases of the experiment. 12B enhanced the leaf area before transplantation and root development after transplantation. FL, R and B induced inferior seedling growth compared to the red–blue-containing LEDs, with B performing poorly in almost all tested parameters. Overall, red, including 11–24% blue, provides the optimum light conditions during the healing stage for the production of high-quality grafted tomato seedlings, with advanced capabilities of abiotic stress adaptation to transplant shock.

Keywords: *Solanum lycopersicon* L.; scion; rootstock; light-emitting diodes; light quality; nursery; growth chamber; photomorphogenesis; root system architecture; antioxidant activity

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1. Introduction

Tomato (*Solanum lycopersicum* L.) is a very popular vegetable worldwide, mostly known for its unique taste and high nutritional value. It constitutes a great source of health-promoting compounds such as minerals and antioxidants such as vitamin C, E, carotenoids, flavonoids and anthocyanins [1]. It is one of the most widely cultivated crops reaching 4.8 million ha globally, almost 500,000 of which were in the E.U., for the period 2010–2019 [2]. Tomato cultivation is mainly established with transplants due to their higher uniformity in size, and well-developed root systems and shoots, leading to constant and high-quality productions with reduced losses compared to seed planting [3].

Transplants might be grafted or nongrafted, although, in the last few decades, grafted transplants have become preferable in the market due to their increased capabilities such as tolerance to soilborne diseases, salinized cultivated lands, drought, heavy metals presence, etc. [3]. Grafting is the union of two intraspecific or interspecific plants or even intrafamilial plant parts, aiming for a successful connection between their vascular bundles

to form one composite organism that functions as a single plant with combined genetic characteristics [4]. The grafting procedure includes four distinguishable stages: (a) the selection of the appropriate combination of a rootstock–scion, (b) the grafting union and connection of the rootstock–scion, (c) healing of the newly grafted plant and (d) hardening of the newly grafted plant [3]. Among the procedure steps, the healing stage of the grafted union is a very crucial process and, thus, requires experienced personnel and specific conditions of relative humidity (>90%), temperature (22–30 °C) and even lighting that favour tissue regeneration and a successful connection between the vascular bundles of the rootstock and scion [5,6]. The stage of healing can be accomplished in environmentally controlled spaces, including growth chambers, where the above-mentioned factors can be adjusted entirely. In addition, market demand for grafted seedlings is high in specific seasons; thus, commercial nurseries face a problem of limited space availability during the healing stage. Therefore, potential time saving through new techniques such as altering the light quality could be essential for saving space and reducing operational costs.

Light is an essential factor in the healing process as numerous cell divisions on the grafting union require a large amount of energy derived through respiration from the consumption of carbohydrates, which are produced in the photosynthesis process controlled by light [7]. Plants receive light radiation and efficiently absorb between wavelengths of 300–750 nm through photoreceptors, and they exhibit various responses depending on their genotype as well as the light intensity, quality, direction and duration [8]. Artificial lighting in horticulture is usually accomplished using fluorescent (FL) lamps, which are used in greenhouses and growth chambers especially due to their high performance and low cost while also having a balanced emission spectrum suitable for plant growing. In the last century, the expanding technology of light-emitting diodes (LEDs) has replaced conventional lamps in almost every artificial lighting application [9]. For example, LEDs are utilized during the healing of grafted watermelon seedlings, which account for over 90% of the total produced watermelon seedlings in some countries (e.g., Japan, Korea, Greece), and grafted tomato seedlings, which account for more than 25% of the total produced tomato seedlings in some countries (Japan, Taiwan, Korea 40%, USA 70%) [3,10]. Relatively narrow-band spectra for matching plants' photoreceptors, production of high light irradiations with low radiant heat and long-life cycles [11] are the major features of LEDs, along with their low energy consumption and small size [12]. According to McCree's study [13], a light environment including high portions of red (600–700 nm) and blue (400–500 nm) wavelengths is ideal for photosynthesis since they are the most photosynthetically efficient parts of the radiation spectra. A recent study involving LEDs for grafted tomato seedlings' production revealed that white comprised of a red/blue (R/B) ratio of 1.2 and a red/far-red (R/FR) ratio of 16 enhanced the transplant quality [14]. In another study with light quality during the healing and acclimatization of grafted tomato seedlings, blue light led to inferior growth compared to red and FL [15].

By the end of a successful grafting process, and the production and distribution of high-quality grafted seedlings, transplantation constitutes another challenge that could limit the crop yield. The transplantation process often diminishes root development of the newly planted seedlings through the destruction of the effective root area and root hairs, resulting in reduced water and nutrient uptake capacity, a phenomenon known as transplant shock [16]. This abiotic stress to plant metabolism is exacerbated when combined with unfavourable soil conditions [17].

The objective of this study was to evaluate the overall quality of grafted tomato seedlings by determining their important physiological and morphological characteristics after their exposure to different light spectra during healing in a chamber. Furthermore, the study aimed to assess the potential after-effect response of the seedlings after their transplantation as affected by different light wavelengths during healing.

2. Materials and Methods

2.1. Plant Material and Growing Conditions

The experiment consisted of two separate phases. The first phase was executed in the facilities of a nursery company (Agris S.A. Kleidi, Imathia, Greece), and the second phase was performed at the greenhouse of the Laboratory of Floriculture of the Aristotle University of Thessaloniki, Greece. All measurements were conducted at the Laboratory of Vegetable Crops of the Aristotle University of Thessaloniki, Greece.

Two tomato (*Solanum lycopersicum* L.) hybrids, "Kabrera F1" and "Emperador F1", were used as scion and rootstock material, respectively. Kabrera F1 hybrid is a popularly grown tomato in Greece, which is usually grafted onto other Solanaceae plants (e.g., tomato and eggplant). Emperador F1 hybrid is a tomato rootstock that provides the scion with tolerance to low temperatures and nematodes. Kabrera × Emperador is a popular grafting combination for grafted tomato seedlings grown in greenhouses in Greece. Tomato seeds of both hybrids were sown in 128-cell plug trays (G.K. Rizakos S.A., Lamia, Greece) containing a 3:1 mixture of peat and vermiculite as substrate.

A schematic representation of the growth of grafted tomato seedlings along with the sampling times in the first and second phases is depicted in Figure 1. After sowing, trays were placed in a germination chamber of favourable conditions of 97% relative humidity and 24 °C temperature in darkness until germination (48–72 h). Upon seedlings' emergence, trays were placed in a Venlo-type greenhouse for 18 days until grafting. Scion seedlings were grown at 18 °C day temperature, while rootstock seedlings were grown at 21.5 °C, all at 60–75% relative humidity. The night temperature was common at 19 °C, and 18 h artificial lighting (100 ± 10 μmol m^{-2} s^{-1}) was supplemented to both hybrids provided by high-pressure sodium lamps (MASTER GreenPower E40, Philips Lighting, Eindhoven, The Netherlands).

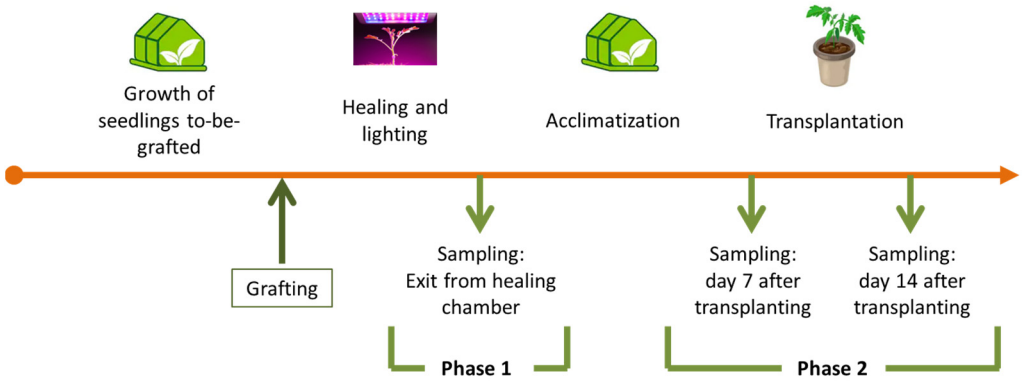

Figure 1. Schematic depiction of the growth of grafted tomato seedlings along with the sampling times in the first and second phases of our experiment.

2.2. Grafting and Healing Process

Eighteen days later, at the stage of two true leaves, scion was grafted on rootstock hybrids through splice grafting, and the plug trays containing the newly grafted seedlings were immediately placed in a healing chamber for six days. Precise environmental conditions of high relative humidity at 90–95% and temperature of 22.5 °C were performed while the air was recirculating.

2.3. Light Treatments in the Healing Chamber (First Phase)

Inside the healing chamber, sole artificial lighting was provided by 5 LEDs or fluorescent lamps mounted on vertically structured shelves (L:2.00 m × W:1.66 m × H:0.76 m). Plug trays were placed on every shelf where one lamp was installed at 30 cm above the plant top. The photoperiod was 18 h, and photosynthetic photon flux density (PPFD) at plant top was 85 μmol m^{-2} s^{-1}, while the LEDs' spectra consisted of narrow-band red (R; peak wavelength at 661 nm), narrow-band blue (B; peak wavelength at 451 nm), two

combinations of RB (12B and 24B) emitting 12% and 24% of blue, respectively, and white (W) emitting 11% of blue. The latter treatment is desirable due to the high colour rendering index (CRI > 50), which facilitates the activities inside the healing chamber. Light treatments' properties and spectral distributions were obtained with a HD 30.1 spectroradiometer (DeltaOhm Srl, Padova, Italy) and are presented in Table 1.

Table 1. Spectral distribution expressed as percentages of total photons reaching the seedling canopy. PPS: phytochrome photostationary state; FL: fluorescent lamps; W: white; B: blue; 24B: 24% blue; 12B: 12% blue; R: red.

Waveband	Light Treatment					
	FL	**W**	**B**	**24B**	**12B**	**R**
Blue%; 400–499 nm	35	11	100	24	12	0
Green%; 500–599 nm	24	18	0	0	0	0
Red%; 600–699 nm	37	70	0	76	88	100
Far-red%; 700–780 nm	4	1	0	0	0	0
PPS	0.82	0.89	0.51	0.89	0.89	0.89

2.4. Acclimatization Process

After the healing process, grafted seedlings were placed into a Venlo-type greenhouse for seven days with a mean temperature of 18 °C and relative humidity of 50–55% and 75–80% at day and night, respectively, for acclimatization. Supplemental artificial lighting was provided by HPS lamps for 18 h daily with a PPFD of 100 ± 10 μmol m^{-2} s^{-1} at the plant top.

2.5. Transplantation (Second Phase)

Seven days later, 25 grafted seedlings per light treatment (150 in total) were transplanted in larger pots (L:7.00 cm × W:7.00 cm × H:6.00 cm) containing a mixture of peat and perlite (2:1) and were placed in a greenhouse. Upon transplantation, seedlings were irrigated with 100 mL of Hoagland's solution [18] until runoff, followed by 20 mL every two days for a total of 14 days.

2.6. Sampling and Measurements

In the first phase of the experiment and upon exiting the healing chamber, ten grafted seedlings per light treatment were sampled randomly, while their quality parameters were evaluated. In the second phase of the experiment, at seven and fourteen days after transplantation, six randomized grafted seedlings per light treatment were sampled and assessed for their qualitative characteristics. These characteristics were suggested by Lee et al. [3] for the definition of grafted tomato seedling quality. Specifically, leaf area was measured using an AM350 area meter (ADC BioScientific Ltd., Hoddesdon, UK), while shoot length (i.e., the length between the apical bud and root collar) and stem diameter below the cotyledons were determined using a digital calliper. In addition, fresh and dry (after three days in an oven at 72 °C) shoot and root weights were measured. Shoot/root (S/R) ratio, shoot dry weight/shoot length (DW/L) ratio, root dry weight/surface area (R/SA) ratio and percentage of root dry weight (%DWR) were also calculated. Chlorophyll fluorescence was determined after 20 min dark adaptation on the first fully developed leaf with a pocket PEA Chlorophyll Fluorimeter (Hansatech Instruments Ltd., Norfolk, UK), and relative chlorophyll content was determined using a CCM-200 plus chlorophyll meter (Opti-Sciences, Hudson, NH, USA). Root growth parameters, including root diameter, root surface area and root length, were obtained through root scanning using a root scanner (EPSON Perfection V700, Nagano, Japan) after their flushing with clean water, and the results were acquired through an image analysis software (WinRHIZO Pro, Regent Instruments Inc., Quebec City, QC, Canada). Moreover, grafted seedlings' leaf lamellae were cooled with liquid nitrogen before their pulverization in a porcelain mortar and eventually stored

at −30 °C for a week. Following this, 2.5 g was extracted into 25 mL 80% aqueous methanol, and total phenolic compounds, as well as total antioxidant capacity, were determined.

2.6.1. Total Phenolic Compounds

Phenolic compounds' concentration in the leaf lamellae extracts was determined according to the Folin–Ciocalteu method [19], where 2.5 mL of Folin–Ciocalteu and 2 mL of 7.5% sodium carbonate solution were added in 0.5 mL of methanolic plant extract and mixed under continuous stirring. The mixture was incubated at 50 °C for 5 min and cooled at room temperature for 3 min, and its absorbance was measured at 760 nm. The results were expressed as g of gallic acid (GAE)/g fresh weight.

2.6.2. Total Antioxidant Capacity (FRAP)

The same methanolic plant extract (from leaf lamellae) was used for the conductance of this method. The ferric reducing antioxidant power (FRAP) assay was produced according to [20], where 250 mL of CH_3COONa buffer solution, 100 mL of TPTZ solution and 100 mL of $FeCl_2$ solution were mixed using a stirrer. Afterwards, 3 mL of this reagent was added to 0.1 mL methanolic plant extract and incubated at 37 °C for 4 min. The absorbance was measured at 593 nm, and the results were expressed as μg of plant extract's FRAP assay.

2.7. Statistical Analysis

Data were statistically analysed using IBM SPSS software (SPSS 23.0, IBM Corp., Armonk, NY, USA). After analysis of variance (ANOVA), post hoc test for comparisons between all the treatments was conducted using the LSD method (unprotected) at significance level $\alpha = 0.05$. Moreover, *t*-test was conducted for the comparison between FL and each LED treatment at significance level $\alpha = 0.05$. The experiment was performed two times, reaching similar conclusions. Herein, the results from the first repetition are presented.

3. Results

3.1. Exit from the Healing Chamber (First Phase)

Shoot length was significantly affected by the different light treatments, as seedlings exposed to W exhibited the highest values compared to the rest of the light treatments, while seedlings under FL were the shortest among all light treatments. Moreover, values in 24B were significantly higher than B and FL. Comparisons using the *t*-test showed that every LED treatment had significantly greater values compared to FL (Figure 2A). Stem diameter was also affected; seedlings under red–blue combinations (24B and 12B) developed the thickest stems, which were significantly greater compared to W and B LEDs. 24B was the only treatment with significantly greater stem diameter compared to FL (Figure 2B). Furthermore, red–blue combinations (24B and 12B) enhanced the seedlings' leaf area compared to R, B and FL (Figure 2C). In contradiction to the above, FL induced the development of a greater DW/L ratio compared to the rest of the light treatments, while B showed significantly lower values compared to 24B and 12B. According to the *t*-test, all LEDs had significantly lower DW/L compared to FL (Figure 2D). Shoot dry weight was greater under W and 24B compared to FL and B, while the latter also showed significantly lower values compared to 12B and R. Moreover, individual *t*-test comparisons showed significant differences between FL and W, 24B, 12B and R (Figure 2E). 24B also promoted root dry weight development compared to FL, B, 12B and R, while the latter showed lower values than W as well (Figure 2F).

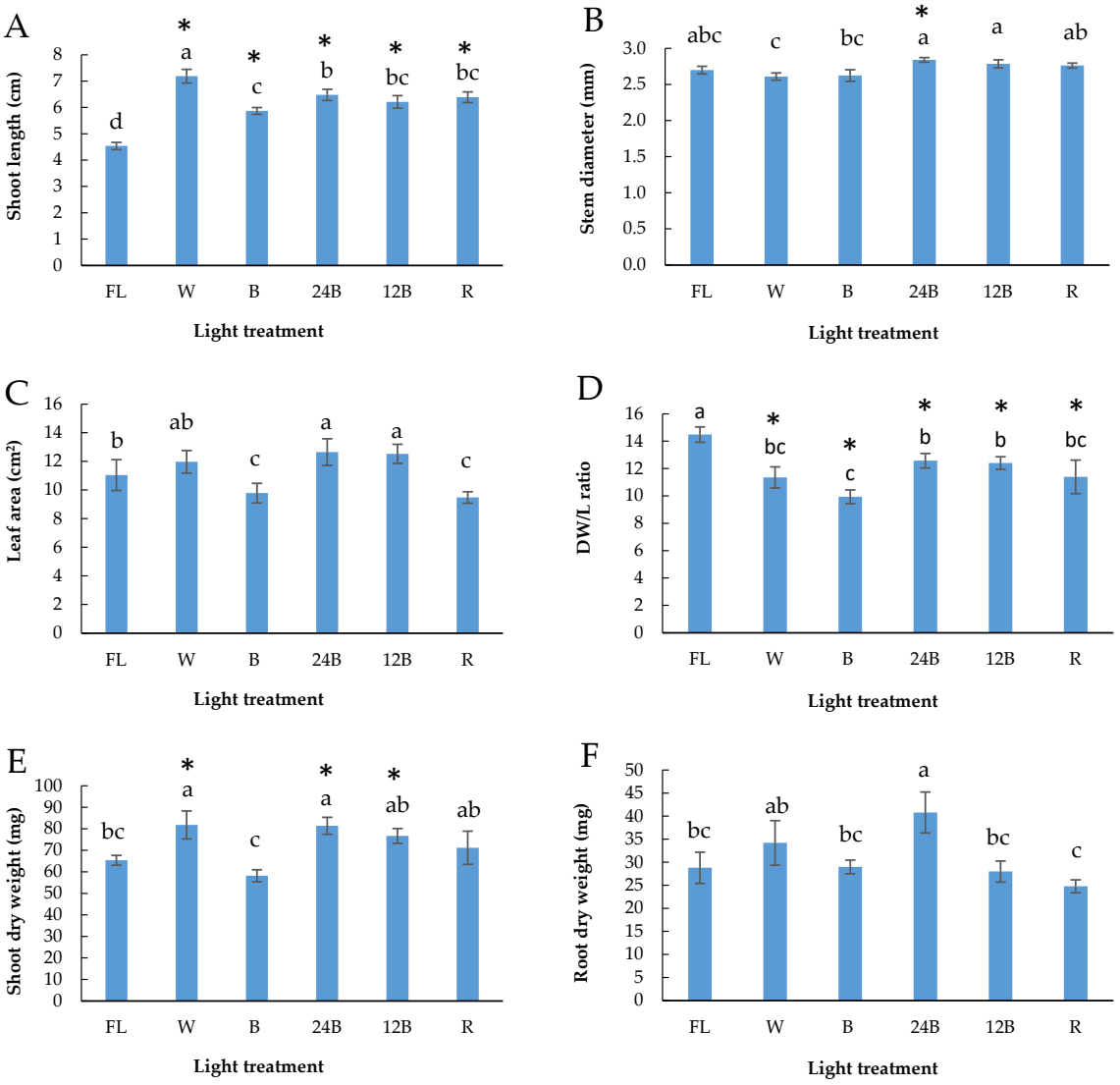

Figure 2. (**A**) Shoot length, (**B**) stem diameter, (**C**) leaf area, (**D**) dry weight/length (DW/L) ratio, (**E**) shoot dry weight and (**F**) root dry weight of 10 grafted tomato seedlings per light treatment after their exposure to six light treatments during healing. Bars (±SE) followed by different letters are significantly different ($p \leq 0.05$) according to the LSD method. Bars (±SE) followed by asterisks indicate significant differences between the LED treatments and the control (FL) at $p \leq 0.05$ according to *t*-test. FL: fluorescent lamps; W: white; B: blue; 24B: 24% blue; 12B: 12% blue; R: red.

3.2. Transplantation (Second Phase)

Seven days after transplantation, 24B enhanced stem diameter compared to FL and R, while 12B led to enhanced values compared to R (Figure 3A). Leaves were significantly expanded under W compared to B, 24B and R (Figure 3B). Shoot dry weight was enhanced under FL and W compared to B, while the latter light treatment also significantly inhibited the root dry weight production compared to FL, W, 24B and 12B (Figure 3C,D). Regarding root architecture analysis, W increased the root length compared to FL, B and R, while the root surface area was also enhanced under W compared to B. Moreover, W and 24B were also greater compared to FL according to the *t*-test (Figure 3E,F). The maximum quantum yield of the primary photochemistry (Fv/Fm) was significantly greater under B compared to 12B (Table 2). However, the total phenolic compounds and FRAP were not significantly affected by the different light treatments (Table 2). R/SA was significantly greater in FL and 24B compared to W, while %DWR at day 7 was not affected by the light treatments (Table 2).

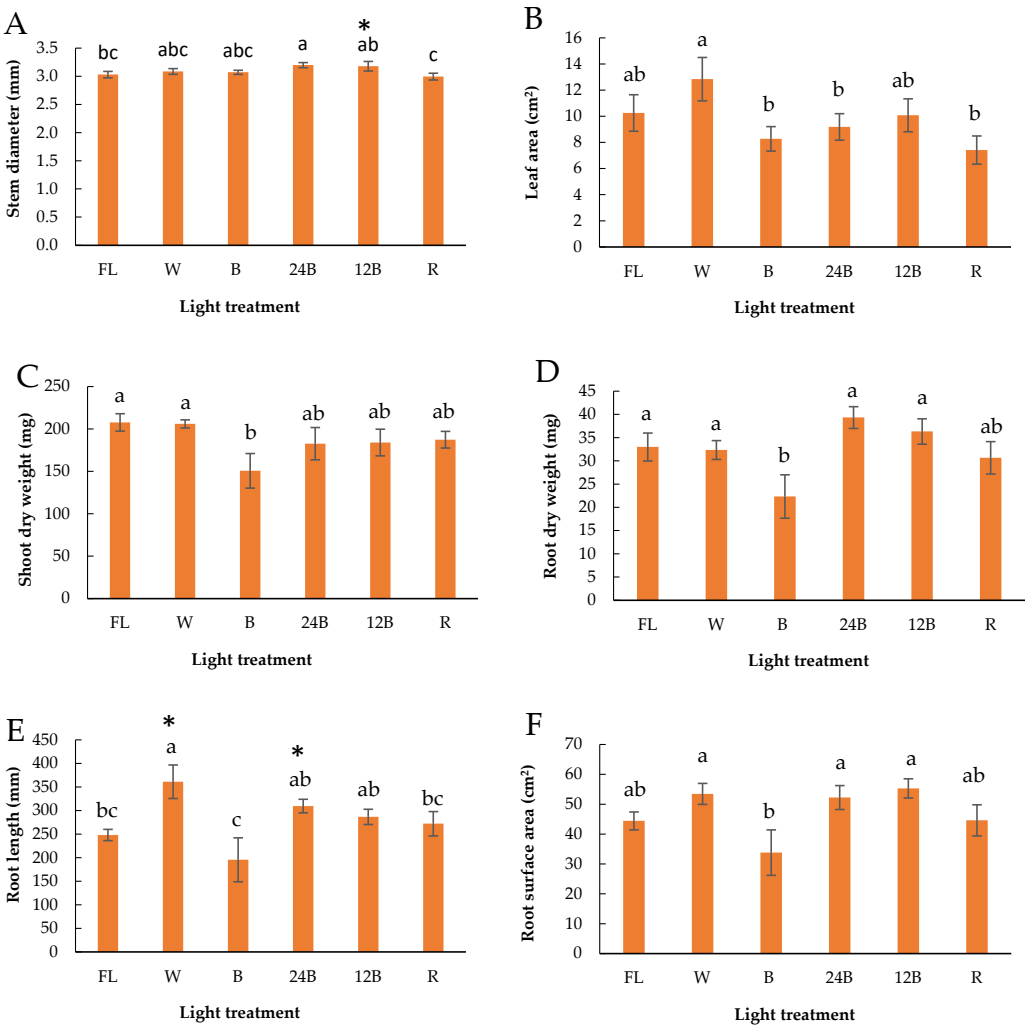

Figure 3. (**A**) Stem diameter, (**B**) leaf area, (**C**) shoot dry weight, (**D**) root dry weight, (**E**) root length and (**F**) root surface area of 6 grafted tomato seedlings per light treatment during healing, 14 days after acclimatization process plus seven days after transplantation. Bars (±SE) followed by different letters are significantly different ($p \leq 0.05$) according to the LSD method. Bars (±SE) followed by asterisks indicate significant differences between the LED treatments and the control (FL) at $p \leq 0.05$ according to *t*-test. FL: fluorescent lamps; W: white; B: blue; 24B: 24% blue; 12B: 12% blue; R: red.

Fourteen days after transplantation, the stem diameter was significantly promoted under R compared to the rest of the light treatments, except for FL, while B showed lower values compared to FL according to the *t*-test (Figure 4A). 12B enhanced leaf area development compared to FL and R (Figure 4B). Shoot dry weight was enhanced by W than B, while the *t*-test also showed greater values for W compared to FL (Figure 4C). Root dry weight was greater under 24B compared to FL, while the *t*-test also showed greater values for W, 24B and R compared to FL (Figure 4D). Roots were significantly longer in W and 24B compared to B (Figure 4E), while no significant differences were observed in the root surface area, except for the *t*-test, which showed greater values in 12B compared to FL (Figure 4F). Fv/Fm was not significantly different among the light treatments, but B and 24B had significantly lower values compared to FL according to the *t*-test (Table 2). The total phenolic compounds were greater under 24B and FL than B (Table 2), while the FRAP was enhanced under 24B compared to R and FL (Table 2). At 14 days, R/SA was not significantly affected, while the %DWR was significantly greater under B compared to FL (Table 2).

Table 2. Effect of light treatment on physiological parameters, biochemical compounds and calculated qualitative parameters of grafted tomato seedlings 7 and 14 days after transplantation. Fv/Fm: maximum quantum yield of primary photochemistry; TPC in mg/kg: total phenolic content; FRAP in µg/g; ferric reducing antioxidant power; R/SA in g/cm^2: root dry weight/surface area; %DWR: percentage of root dry weight; FL: fluorescent lamps; W: white; B: blue; 24B: 24% blue; 12B: 12% blue; R: red. Mean values followed by different letters are significantly different at $p \leq 0.05$ according to the LSD method. Asterisks indicate significant differences between the LED treatments and the control (FL) at $p \leq 0.05$ according to *t*-test.

Parameter	Light Treatment						
	FL	W	B	24B	12B	R	*p*-Value
Fv/Fm d7	0.84 ± 0.00 ^{ab}	0.84 ± 0.00 ^{ab}	0.84 ± 0.00 ^{a}	0.84 ± 0.00 ^{ab}	0.83 ± 0.00 ^{b}	0.84 ± 0.00 ^{ab}	0.136
Fv/Fm d14	0.81 ± 0.00 ^{a}	0.80 ± 0.01 ^{a}	0.80 ± 0.00 ^{a,*}	0.80 ± 0.00 ^{a,*}	0.81 ± 0.00 ^{a}	0.81 ± 0.00 ^{a}	0.509
TPC d7	0.33 ± 0.03 ^{a}	0.29 ± 0.03 ^{a}	0.30 ± 0.01 ^{a}	0.34 ± 0.01 ^{a}	0.29 ± 0.01 ^{a}	0.32 ± 0.02 ^{a}	0.435
TPC d14	0.30 ± 0.01 ^{a}	0.28 ± 0.01 ^{ab}	0.25 ± 0.00 ^{b,*}	0.29 ± 0.03 ^{a}	0.26 ± 0.01 ^{ab}	0.28 ± 0.00 ^{ab}	0.060
FRAP d7	155.6 ± 7.1 ^{a}	168.1 ± 6.0 ^{a}	162.3 ± 17.7 ^{a}	165.6 ± 1.8 ^{a}	166.9 ± 3.6 ^{a}	168.1 ± 5.5 ^{a}	0.866
FRAP d14	146.5 ± 5.1 ^{c}	166.4 ± 8.7 ^{abc}	165.5 ± 8.3 ^{abc}	179.1 ± 6.8 ^{a,*}	171.4 ± 7.5 ^{ab}	152.4 ± 2.4 ^{bc}	0.048
R/SA d7	0.74 ± 0.02 ^{a}	0.61 ± 0.01 ^{b,*}	0.68 ± 0.07 ^{ab}	0.71 ± 0.02 ^{a}	0.70 ± 0.01 ^{ab}	0.69 ± 0.02 ^{ab}	0.085
R/SA d14	0.57 ± 0.01 ^{a}	0.63 ± 0.03 ^{a}	0.64 ± 0.03 ^{a}	0.73 ± 0.09 ^{a}	0.56 ± 0.11 ^{a}	0.62 ± 0.03 ^{a}	0.430
%DWR d7	13.8 ± 1.4 ^{a}	13.6 ± 0.9 ^{a}	13.7 ± 4.2 ^{a}	17.8 ± 0.8 ^{a}	16.5 ± 0.2 ^{a}	14.0 ± 0.8 ^{a}	0.459
%DWR d14	9.4 ± 0.1 ^{b}	10.3 ± 0.5 ^{ab}	13.0 ± 2.2 ^{a,*}	12.3 ± 1.0 ^{ab}	11.1 ± 1.2 ^{ab}	10.6 ± 0.5 ^{ab}	0.115

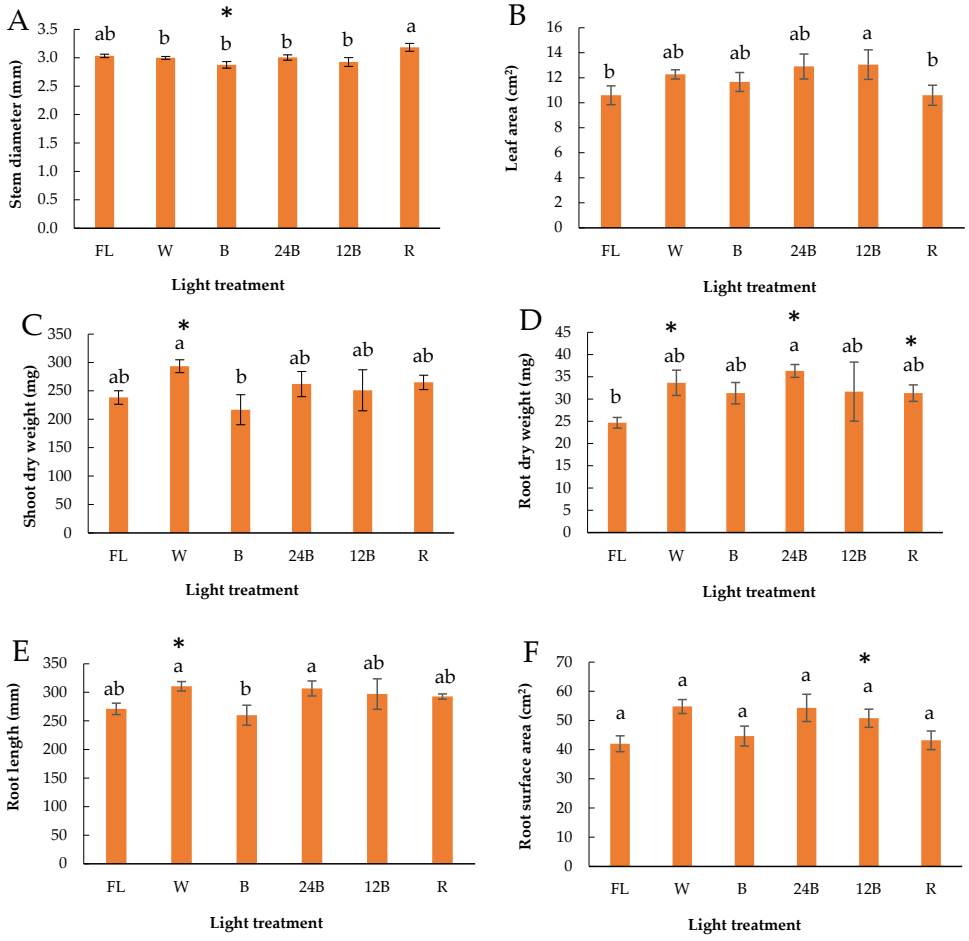

Figure 4. (**A**) Stem diameter, (**B**) leaf area, (**C**) shoot dry weight, (**D**) root dry weight, (**E**) root length and (**F**) root surface area of 6 grafted tomato seedlings per light treatment during healing, 14 days after acclimatization process plus 14 days after transplantation. Bars (±SE) followed by different letters are significantly different ($p \leq 0.05$) according to the LSD method. Bars (±SE) followed by asterisks indicate significant differences between the LED treatments and the control (FL) at $p \leq 0.05$ according to *t*-test. FL: fluorescent lamps; W: white; B: blue; 24B: 24% blue; 12B: 12% blue; R: red.

4. Discussion

The seedling production industry and market require the production of high-quality grafted seedlings. Seedlings of optimum morphological and physiological characteristics exhibit faster plant development and uniformity along with better transplantation success, thus leading to high, standard yields of excellent quality and marketable profit [3]. Subsequently, it is crucial to ensure the development of appropriate methods, including specific conditions during the healing process, along with selecting suitable light spectra for the proper development of high-quality grafted seedlings with the minimum possible cost and the lowest environmental impact. The introduction of LEDs in seedlings' production during the healing stage constitutes a highly efficient, nonchemical, sustainable solution for plant development regulation and quality enhancement [21].

LED is a significantly more expensive technology per photosynthetic photon compared to traditional light sources; thus, economic viability is based on decreased electric costs due to enhanced fixture efficiency. Among the important benefits of LED technology, the highly focused radiation can lead to the light reaching the plants with considerable efficiency and subsequently leading to reduced electricity costs [22].

4.1. Exit from the Healing Chamber (First Phase)

Significant differences were recorded among light treatments in the majority of the evaluated parameters. It is obvious that treatments with an increased red light portion enhanced stem elongation through phytochromes, as reported by Li et al. [23]. In addition, blue light is known to decelerate stem elongation [24]. These findings agree with Javanmardi and Emami [25], who reported tomato and pepper seedlings' shoot elongation under LED light spectra compared to narrow-band blue and red and their combinations, as well as with Głowacka's [26] findings of an inhibiting effect of blue light on tomato transplant growth. Phytochromes (the red and far-red photoreceptors) and cryptochromes (the blue photoreceptors) are responsible for the so-called shade-avoidance responses, including stem elongation. A reduction in the R/FR ratio alters the level of phytochrome B leading to the activation of Phytochrome Interacting Factors (PIFs), and subsequently increasing the auxins' level [27].

Stem diameter was significantly enhanced under combinations of red and blue wavelengths (mainly 12B and 24B) compared to B, as reported by Hernandez et al. [28] in their study with grafted tomato seedlings exposed to different light wavelengths in a plant factory. Similar results were recorded on leaf area under 12B and 24B, which showed a beneficial effect compared to B and R spectra, in agreement with Ouzounis et al.'s [29] reports about the additive effect of red and blue light in leaf expansion. Both stem diameter and leaf area have been characterized as valuable quality indices for the determination of grafted watermelon seedling quality after the healing stage [30].

DW/L has been suggested as an efficient indicator of grafted tomato seedlings' quality [3], as also stated for grafted watermelon [30]. In our case, FL exhibited considerable DW/L, but both incorporated parameters, shoot dry weight and shoot length, were inferior compared to other light treatments. We concluded that seedlings treated with FL indeed reached a high quality but showed a much slower growth rate. Among the LEDs, B showed inferior DW/L, reaffirming the low quality displayed by other quality parameters such as stem diameter, leaf area and root dry weight.

Indeed, seedlings treated with B exhibited inferior shoot and root biomass formation compared to red–blue treatments and especially 24B. In green tissues, blue wavelengths are mainly absorbed by carotenoids and anthocyanins, which are not efficient energy transducers of the photosynthetic apparatus [31]. On the contrary, red light drives photosynthesis in a more efficient manner, while blue mediates photomorphogenic processes [8].

4.2. Transplantation (Second Phase)

Seven days after transplantation, stem diameter was greater under a combination of red–blue (24B) compared to monochromatic red light, as also reported by Li et al. [23], who

studied tomato seedlings' responses under six different light treatments for 30 days in an artificial climate chamber. Conversely, R significantly improved stem diameter 14 days after transplantation. It is possible that the long-term effects of light wavelengths could be contrasting compared to the effects during or immediately after plant exposure.

The leaf area of transplanted tomato seedlings was significantly enhanced by W after 7 days and 12B after 14 days from transplantation. Both light treatments emit a significant portion of red light (83–88%) supplemented with 11–12% blue, leading to the conclusion that red–blue wavelengths are beneficial for the growth and development of plant tissues, at least during the first stages of plant growth. These results are in agreement with a study involving cucumber supporting the beneficial effect of red and blue combinations on seedlings' development compared to monochromatic red light [32]. This conclusion is associated with chlorophyll pigments, which mainly absorb blue and red wavelengths; thus, red–blue combinations comprise a highly efficient, complete light source. Conversely, Wu et al. [33] reported that a sole red LED light imposed a beneficial effect on leaf area expansion compared to a white LED light.

The B wavelength decelerated the shoot and root biomass production both at 7 and 14 days after transplantation, except for the root dry weight at 14 days. Regarding the analysis of the root architecture after transplantation, the image is similar to the previously reported results. As a general rule, B induced the development of the least expanded root system as displayed by the shorter total root length and the lowest root surface values (the latter only at seven days after transplantation). Conversely, LEDs containing red and blue wavelengths enhanced the root system development. These observations highlight the long-term effect of sole blue light spectra on the inhibition of cell expansion and division [34]. Similarly, a study with cucumber showed that the dry shoot mass was enhanced under red light supplemented with blue [35].

All plants were healthy at both time intervals after transplantation, as shown by the high Fv/Fm values (0.80–0.84). Björkman and Demmig [36] stated that values of 0.78–0.86 are indicative of healthy plants with efficient photosynthetic activity.

Plants produce and accumulate secondary metabolites such as phenolic compounds as a response to several biotic and abiotic stressful situations. In some cases, light quality can impose significant stress on plant tissues, thus leading to the increased biosynthesis of such compounds [37]. Phenolics are antioxidant compounds associated with the scavenging of reactive oxygen species. It is assumed that an increased antioxidant capacity may be related to sturdier and better acclimated plants, which may show enhanced vegetative growth in the long run. In our study, transplanted tomato seedlings showed increased phenolic compounds and antioxidant capacity under 24B, indicating the necessity of both red and blue wavelengths in specific portions for enhanced plant development and quality. Similarly to our results, a 70% red/30% blue treatment led to the increased phenolic content of lamb's lettuce compared with monochromatic red and blue [38], while spinach did not show significant differences in total phenolics and antioxidants when grown under broad-spectra light treatments [39].

Overall, individual comparisons showed that FL performed similar to B leading to the production of seedlings with poor capacity to intercept light (i.e., leaf area), and thus lower overground and underground biomass production. This effect was continued after transplantation in the greenhouse when both light treatments, and especially B, showed inferior root development. Conversely, LED treatments emitting relatively high amounts of red light favoured the production of seedlings with greater potential to overcome the transplanting shock and develop into plants with a vast root system. This study revealed potential research gaps that require further research and attention. For example, the experimental procedure can also be applied for different scion–rootstock hybrid combinations, or even for different species with the ability to be grafted. Moreover, light quality is known to affect the flowering of plants; thus, field or greenhouse cultivation would enhance our understanding of the potential after-effect of light quality on flowering and even crop yield and quality.

5. Conclusions

B performed poorly in almost all tested parameters in both experiment phases, reaffirming the wavelength's inhibitory effect on plant growth when used alone. R also induced inferior seedling growth compared to red–blue-containing LEDs, but not as much as B, indicating the increased importance of the red wavelength for plant growth compared to blue. Seedling growth was also decelerated under FL compared to red–blue-containing LEDs proving once more the superiority of the latter light source for the production of high-quality seedlings due to better spectral distribution. Overall, LED treatments emitting at least a portion of red and blue wavelengths (i.e., W, 12B and 24B) enhanced several developmental characteristics of grafted tomato seedlings after healing and up to 14 days from transplantation. It is concluded that red, including 11–24% blue provides the optimum light conditions during the healing stage for the production of high-quality grafted tomato seedlings, including higher antioxidant activity and abiotic stress adaptation to transplant shock. The addition of a small portion of green light in the latter wavelength is optional but beneficial for the visualization of white light, which facilitates scouting in the healing chamber.

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