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ARTICLE

Optimizing Cherry Tomato Growth under Heat Stress Using Semi-Enclosed Greenhouses and LED Spectra

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ABSTRACT: High solar radiation during the Thai summer raises greenhouse temperatures to 33–41°C, exceeding the optimal range for tomato cultivation (15–25°C) and reducing yield and fruit quality. This study aimed to evaluate the effectiveness of combining daytime shading with evening supplemental light-emitting diode (LED) lighting to improve the growth, yield, and fruit quality of cherry tomato grown under heat-stress conditions. To alleviate excessive heat accumulation, a semi-enclosed greenhouse equipped with an 80% shade net was applied from 11:00 to 14:00, while supplemental LED lighting was provided from 18:00 to 22:00. Plants were exposed to red, blue, red–blue, and red–blue–white (3000 K) light spectra at intensities of 150 and 200 μmol m^{-2} s^{-1}. Growth parameters, biomass accumulation, fruit yield, and fruit quality attributes were evaluated throughout the cultivation period. The results demonstrated that supplemental LED lighting significantly improved plant performance under shaded greenhouse conditions. Among all treatments, the combined red–blue spectrum (3:1) supplemented with white light at an intensity of 200 μmol m^{-2} s^{-1} produced the most favorable response. Plants grown under this treatment exhibited greater vegetative growth, increased shoot and root biomass, enhanced flowering and fruit set, and higher total fruit yield compared with the control treatment without supplemental lighting. In addition, fruit quality was improved, as evidenced by increased soluble solids content (°Brix), indicating enhanced sweetness and market value. The improved performance was attributed to increased photosynthetic efficiency and better light utilization during the evening period. These findings suggest that integrating daytime shading with targeted evening LED supplementation is an effective strategy for mitigating heat stress and maintaining high productivity of greenhouse-grown cherry tomatoes under tropical environmental conditions in Thailand.

KEYWORDS: Heat stress; semi-enclosed greenhouses; light-emitting diodes spectra

1 Introduction

Climate change has become one of the most significant challenges affecting global agricultural production. The continuous increase in greenhouse gas (GHG) emissions associated with industrialization and other human activities has accelerated global warming, resulting in a rise in the Earth's average surface temperature of approximately 0.9°C since the nineteenth century. Current climate projections indicate that global temperatures may increase by as much as 1.5°C by the middle of this century if emissions continue at the present rate. Such environmental changes have already caused considerable disruptions to terrestrial, freshwater, and marine ecosystems, with many impacts expected to be long-lasting or irreversible [1]. The greenhouse effect, resulting from the accumulation of atmospheric gases that absorb outgoing infrared radiation, is the principal mechanism responsible for this warming trend. Major anthropogenic sources of

GHG emissions include fossil fuel consumption, intensive agricultural practices, nitrogen fertilizer application, land-use conversion, biomass burning, livestock production, and manure management. Consequently, climate change is increasingly influencing agricultural productivity through its effects on crop growth, soil properties, pest pressure, and livestock production. Cherry tomato (*Solanum lycopersicum var. cerasiforme*) is an economically important horticultural crop in Thailand because of its widespread consumption as both a fresh vegetable and a cooking ingredient [2,3]. Compared with conventional tomatoes, cherry tomatoes generally contain higher soluble solids, typically ranging from 8 to 10°Brix, making them more attractive to consumers seeking sweeter fruits [4]. Their premium market price, approximately US$2.35–2.94 kg^{-1}, further enhances their commercial value [5]. However, domestic production depends largely on imported seed materials, primarily originating from South America [6]. Optimal cultivation of cherry tomato requires relatively cool environmental conditions, with temperatures between 15°C and 25°C, relative humidity of approximately 70%–80%, and sufficient solar radiation. In Thailand, cultivation is generally conducted during three seasonal periods, with the second production cycle (mid-February to late April) coinciding with the hottest months of the year. During this period, greenhouse temperatures frequently increase to 33°C–41°C, exposing plants to severe heat stress. Excessive temperature and solar radiation adversely affect reproductive development by reducing flower initiation, increasing flower abscission, and ultimately decreasing fruit yield and quality [7,8]. Several environmental control strategies have been developed to alleviate heat stress in protected cultivation systems. Among these, semi-enclosed greenhouses equipped with movable shade nets are widely used to reduce incoming solar radiation during periods of maximum heat load, particularly between 11:00 and 14:00 h. Although this approach effectively decreases greenhouse temperature, it simultaneously limits photosynthetically active radiation (PAR), thereby reducing the amount of light available for carbon assimilation. One practical strategy for compensating this reduction is the application of supplemental lighting during the evening period, which extends the daily photoperiod and maintains photosynthetic activity after sunset. Previous studies have demonstrated that appropriately selected light spectra can improve vegetative growth, carbohydrate accumulation, and fruit quality while increasing soluble sugar concentrations to approximately 11–12°Brix. In particular, red, blue, and white wavelengths play complementary roles in regulating photosynthesis, chlorophyll synthesis, plant architecture, and fruit development, although inappropriate spectral composition or excessive light exposure may induce physiological stress [9]. Compared with conventional artificial lighting technologies, including fluorescent lamps, incandescent bulbs, and high-pressure sodium (HPS) lamps, light-emitting diode (LED) technology provides substantial advantages in terms of energy efficiency, spectral flexibility, lower heat emission, and longer operational lifetime, often exceeding 50,000 h [10–15]. These characteristics have promoted the widespread adoption of LEDs in greenhouse crop production. Nevertheless, the effectiveness of supplemental lighting depends on several interacting factors, including wavelength composition, light intensity, photoperiod, radiation uniformity, energy consumption, and fixture placement. Properly designed LED lighting systems have been reported to enhance chloroplast function, improve photosynthetic efficiency, stimulate carbohydrate biosynthesis, and accelerate fruit maturation [16]. During fruit ripening, enhanced light availability promotes the conversion of starch into soluble sugars through coordinated regulation of plastid development, carbohydrate-metabolism enzymes, and the expression of genes involved in carbon metabolism [16–19]. Improved light conditions also stimulate the biosynthesis of carotenoids, particularly lycopene and β-carotene, thereby contributing to improved nutritional quality and market value of tomato fruits [20–24]. Collectively, these findings highlight the importance of optimizing both light quality and light intensity, especially red and blue wavelengths, for greenhouse tomato production [15,25]. Despite these advances, greenhouse tomato production in tropical regions continues to face unique challenges.

Growers commonly rely on shade nets, natural ventilation, evaporative cooling, and irrigation management to reduce heat stress during summer cultivation. While these approaches effectively decrease canopy temperature, they also reduce available PAR and may consequently limit photosynthetic performance and crop productivity. Although supplemental LED lighting has been extensively investigated under temperate greenhouse conditions, relatively little information is available regarding its integration with daytime heat-mitigation strategies under tropical environments. Furthermore, previous research has generally examined either shading techniques or supplemental lighting independently, whereas studies evaluating their combined effects remain limited.

Therefore, this study investigated the influence of four supplemental LED spectral compositions, namely red, blue, red–blue, and red–blue–white (3000 K), applied at photosynthetic photon flux densities of 150 and 200 μmol m^{-2} s^{-1} for 4 h each evening in a semi-enclosed greenhouse. Plant growth, biomass accumulation, fruit yield, and fruit quality, including lycopene, vitamin C, total phenolic compounds, and chlorophyll content, were evaluated throughout a 90-day cultivation period. We hypothesized that integrating daytime shade-net cooling with evening supplemental LED lighting would improve photosynthetic performance under tropical summer conditions and that the combined red–blue–white spectrum would provide superior plant growth, yield, and fruit quality compared with monochromatic or dual-spectrum lighting treatments. The principal novelty of this research is the development of an integrated greenhouse lighting strategy that combines daytime heat mitigation with targeted evening LED supplementation to enhance cherry tomato production under high-temperature tropical environments.

2 Material and Methods

2.1 Experimental Site and Seed Acquisition

The experiment was conducted in four identical semi-enclosed greenhouse compartments, each measuring 10 m × 6 m × 3.5 m (60 m^2). The four greenhouse compartments were arranged side by side, resulting in a total experimental area of approximately 6 m × 24 m (144 m^2). One greenhouse compartment served as the control greenhouse, while the remaining three greenhouse compartments were used as experimental units. The experimental greenhouses were equipped with an opaque 80% shade net (Fig. 1) that was deployed daily from 10:00 to 14:00 h to reduce excessive solar radiation and heat stress. After 14:00 h, the shade net was retracted to allow normal sunlight exposure. The experiment was conducted from 25 February to 28 May 2025.

Figure 1: Semi-enclosed greenhouse used in the experiment.

Cherry tomato (*Solanum lycopersicum* var. *cerasiforme*) cultivar ‘Kingfisher’ (Nakhonseeds Co., Ltd.) was used in this study. A total of 300 seeds were sown in 50 cell seedling trays (27.5 cm × 53.5 cm × 5.5 cm). The seedlings were irrigated regularly for 25 days–30 days until four to five true leaves had developed.

Subsequently, uniform seedlings were transplanted into planting pots with a diameter of 10 inches and a depth of 30 cm. Each pot was filled with a growing medium consisting of topsoil, composted manure, and black rice husk mixed at a ratio of 3:1:1. A compound fertilizer (15–15–15) was applied at a rate of 25 g m^{-2} at 15-day intervals. Drip irrigation was supplied at a flow rate of 2 L h^{-1}, with watering conducted twice daily (morning and afternoon).

2.2 Experimental Design

A total of 160 potted tomato plants were assigned to the supplemental LED treatments, while 60 plants grown in the control greenhouse (20 plants × 3 replicates) served as the control treatment. The control plants were cultivated under natural sunlight without shade-net management or supplemental LED lighting. The experiment was conducted using a completely randomized design with three biological replicates, corresponding to the three experimental greenhouse compartments. within each greenhouse, eight supplemental LED treatments (A150, A200, B150, B200, C150, C200, D150, and D200) were arranged in separate sections. Opaque blackout curtains were installed between adjacent treatment sections to prevent light contamination among different LED spectra. The overall experimental layout is illustrated in Fig. 2. The experimental design and study site were developed in collaboration with a local community enterprise. The greenhouses were modified into semi-enclosed systems and equipped with a supplemental lighting system. Seed propagation and planting practices followed standard local agricultural methods. The supplemental lighting treatments consisted of four spectral compositions: A = red LED, B = blue LED, C = red + blue LED (red = 3:1), and D = red + blue + white LED (red:blue = 3:1:1). Each spectral composition was supplied at two photosynthetic photon flux densities (PPFD), namely 150 and 200 µmol m^{-2} s^{-1}, resulting in eight supplemental lighting treatments (A150, A200, B150, B200, C150, C200, D150, and D200). Two supplemental light intensities (150 and 200 µmol m^{-2} s^{-1} PPFD) were selected to evaluate the effects of moderate and high supplemental lighting on tomato growth and fruit quality under shaded greenhouse conditions. Supplemental lighting was provided daily from 18:00 to 22:00 h. The LED fixtures were positioned 30 cm above the plant canopy during the first 45 days after transplanting and were subsequently adjusted to 15 cm above the canopy to maintain the target light intensity as the plants grew.

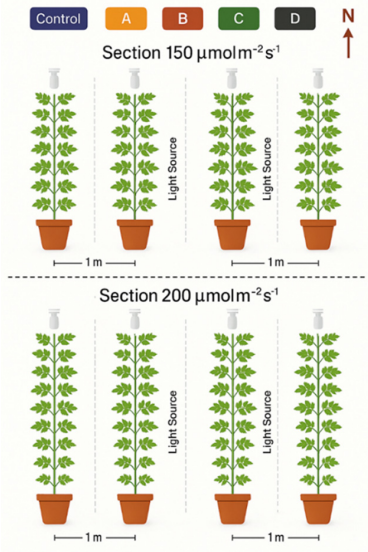


Figure 2: Lay out of tomato plant treatment groups by experimental zones with light intensity of 150 µmol m^{-2} s^{-1} and 200 µmol m^{-2} s^{-1}.

The specific details of the experimental set-ups are as follows: The control group was not provided with supplemental light from 18:00 to 22:00. Natural light was provided through the entire experiment except between 10:00 and 14:00. The control greenhouse represented the conventional cultivation practice under natural sunlight without shade-net coverage or supplemental LED lighting and served as the baseline treatment for comparison with all supplemental LED treatments.

A150 was exposed to red light with an intensity of 150 μmol m^{-2} s^{-1}.

B150 was exposed to blue light with an intensity of 150 μmol m^{-2} s^{-1}.

C150 was exposed to a consolidation of red and blue wavelengths (3:1) with an intensity of 150 μmol m^{-2} s^{-1}.

D150 was exposed to the consolidation of red and blue wavelengths and white light at 3000 K with an intensity of 150 μmol m^{-2} s^{-1}.

A200 was exposed to red light with an intensity of 200 μmol m^{-2} s^{-1}.

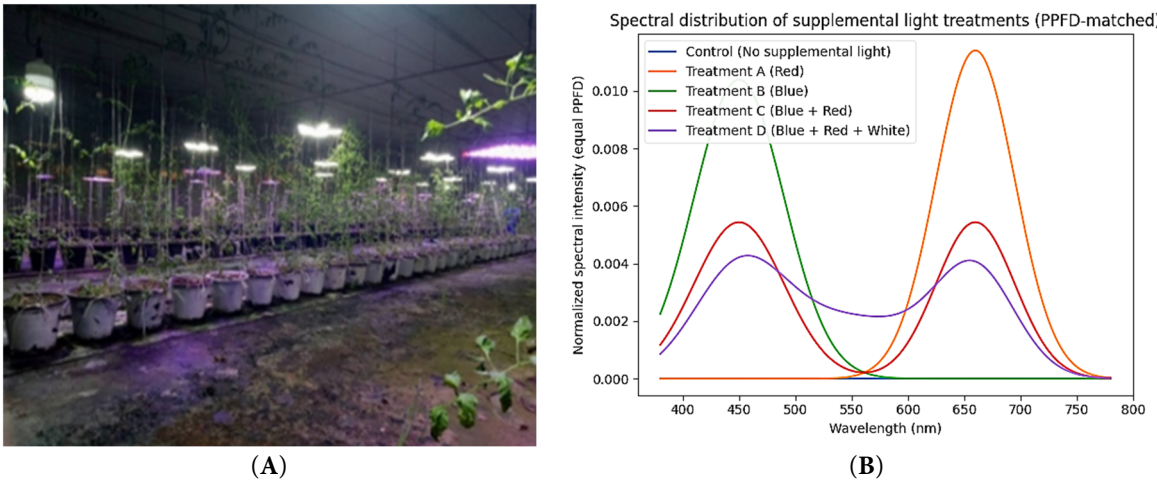
B200 was exposed to blue light with an intensity of 200 μmol m^{-2} s^{-1}.

C200 was exposed to a consolidation of red and blue wavelengths (3:1) with an intensity of 200 μmol m^{-2} s^{-1}.

D200 was exposed to the consolidation of red and blue wavelengths (3:1:1) and white light at 3000 K with an intensity of 200 μmol m^{-2} s^{-1}.

Supplemental light was provided for A, B, C, and D treatments for 4 h a day from 18:00 to 22:00 throughout the 90 days growing period to stimulate the formation of tomato flowers.

The photosynthetically active radiation of supplemental light (Fig. 3A) in the blue (400 nm–500 nm) and red wavelengths (600 nm–700 nm) was provided 4 h every day, from 18:00 to 22:00.



(**A**) (**B**)

Figure 3: Series of light waves in the greenhouse to the tomatoes during 18:00–22:00. (**A**) and Spectral distribution of supplemental light treatments used in the experiment (**B**).

Spectral distribution of supplemental light treatments (Fig. 3B) used in the experiment. The control treatment received no supplemental light. Treatments A, B, and C were exposed to blue, red, and combined blue red light, respectively, while treatment D consisted of a combination of blue, red, and white light. The curves represent relative spectral intensity across the photosynthetically active radiation (PAR) range.

The plant record reader for light intensity sensors position is illustrated in Fig. 4 had a photosynthetic photon flux density (PPFD) measurement accuracy of ±5%, a humidity accuracy of ±2%, and a temperature accuracy of ±0.3°C. Light intensity sensors were positioned between planting rows at canopy level within each treatment section. The sensor height was periodically adjusted to maintain canopy level as plant

height increased, ensuring that the target photosynthetic photon flux density (PPFD) was consistently maintained throughout the experimental period.

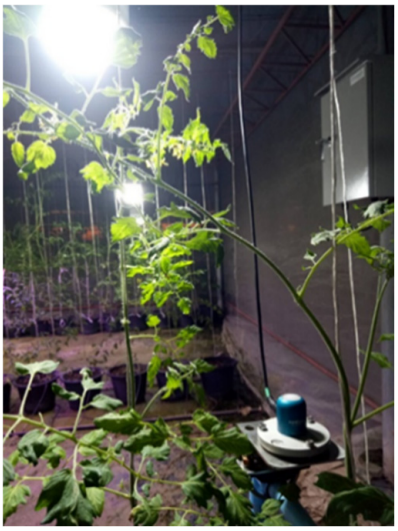


Figure 4: Light intensity sensor in the greenhouse.

Temperature Monitoring in the Greenhouse: Greenhouse temperature was continuously monitored from planting in February 2025 until harvest in May 2025 (Table 1). Ambient temperatures during the initial growth stage in February ranged from 31 to 41°C, coinciding with early seedling development. Following the onset of the rainy season, greenhouse temperatures generally decreased and remained below 40°C. Tomato harvesting occurred during this cooler period.

Table 1: Temperature and light intensity (PPFD, μmol m^{-2} s^{-1}) in the greenhouse during February–May 2025.

Month	Temperature (°C)	Intensity Light (PPFD) (μmol m^{-2} s^{-1})
February	35–41	303–682
March	37–43	384–788
April	29–41	408–801
May	31–40	512–1402

Measurement of supplemental light intensity in the greenhouse: In this study, photosynthetic photon flux density (PPFD) emitted from light-emitting diode (LED) sources were measured using calibrated instruments, including a PPFD meter and a spectroradiometer. PPFD represents the photon flux available for photosynthesis within the photosynthetically active radiation (PAR) range of 400 nm–700 nm. and is expressed in units of μmol m^{-2} s^{-1}. Light intensity within the greenhouse was monitored from the planting stage through to harvest (Table 1). In early February 2025, prior to installation of the supplemental lighting system, the average light intensity remained below 200 μmol m^{-2} s^{-1}. Following installation of the LED system in mid-February 2025, the average measured light intensity increased substantially to 303 μmol m^{-2} s^{-1}–682 μmol m^{-2} s^{-1}. Higher light intensities were subsequently recorded in March (384 μmol m^{-2} s^{-1}–788 μmol m^{-2} s^{-1}), April (408 μmol m^{-2} s^{-1}–801 μmol m^{-2} s^{-1}), and May (512 μmol m^{-2} s^{-1}–1402 μmol m^{-2} s^{-1}). Seasonal variation also influenced light availability. During the

rainy season, increased cloud cover reduced natural solar radiation entering the greenhouse, thereby affecting overall light intensity.

2.3 Data Collection

The following growth and fruit quality parameters were measured for tomato plants.

1. Fresh Stem and Root Weight: Fresh stem and root weights (g) were determined immediately after harvest using a digital analytical balance.
2. Fruit Yield (fruit weight per plant): Tomato yield was recorded as the total fresh fruit weight per plant (g plant^{-1}) at harvest.
3. Sweetness Measurements (°Brix): Sweetness and acidity were evaluated through total soluble solids (TSS), titratable acidity (TTA), and the sugar–acid ratio.

   (1) Total dissolved solids (TSS) were determined according to the method described by Tigist et al., (2013) [26]. A portion of the tomato juice was extracted using a pulp separator and filtered through cheesecloth. TSS was determined by placing 1 to 2 drops of clear water on the prism of a portable digital refractometer (ATAGO PAL-α Cat. No. 3840, Tokyo, Japan). The result was expressed in degrees Brix, which reflects the sugar concentration in the fruit. The prism of the refractometer was washed with distilled water and dried between samples.

   (2) Titratable acidity (TTA), expressed as percentage of citric acid, was determined according to the method described by Tigist et al., (2013) [26]. Tomato juice (10 mL) was titrated using 0.1 N NaOH to an endpoint of pH 8.2 using a digital pH meter. The volume titrated at 0.1 N NaOH was recorded, and the acidity was calculated as percentage of citric acid (% of tomato juice) using the following formula (Eqs. (1) and (2)):

   $$\text{The titrable acidity (\%)} = \text{volume of NaOH (mL)} \times \text{acid factor volume of juice (mL)} \times 100 \quad (1)$$

   *Citric acid factor = 0.0064.

   (3) The sugar-acid ratio, also known as the ripeness index, is calculated by dividing the total soluble solids (TSS) by the titratable acidity (TTA) of the given sample under analysis:

   $$\text{The sugar acid ratio} = \text{Brix value Percentage acid} \quad (2)$$

4. Lycopene: A mixture consisting of 1 mL of tomato extract and 10 mL of extraction solvent was shaken thoroughly and allowed to stand for 10 min. Subsequently, 1 mL of distilled water was added, shaken again, and allowed to stand for an additional 10 min to facilitate phase separation. The absorbance of the upper hexane layer was measured at 503 nm using a microplate reader (Synergy™ HT Multi-Mode, BioTek Instruments Inc., USA). Measurements were performed in triplicate. Lycopene concentration was calculated using the Eq. (3):

   $$\text{Lycopene (micrograms per milliliter)} = \text{A503} \times 137.4 \quad (3)$$

   A503 refers to the absorbance value of the sample at a wavelength of 503 nm [27].
5. Vitamin C: Vitamin C (ascorbic acid) content was determined following a modified method of Demiray et al. [28]. A 0.1 mL aliquot of tomato juice was mixed with 2.9 mL of 1% (w/v) metaphosphoric acid solution and thoroughly homogenized. The mixture was centrifuged using a Universal Centrifuge

(Z326K, HERMLE Labortechnik GmbH, Germany) at 6000 rpm for 10 min at 4°C to separate the precipitate. The supernatant was filtered through a 0.45 μm membrane filter prior to analysis. Vitamin C content was quantified using high-performance liquid chromatography (HPLC) (LC 1200 Series, Agilent Technologies, Germany) equipped with an Eclipse XDB-C18 column (Agilent Technologies). The mobile phase consisted of distilled water adjusted to pH 3.0 with phosphoric acid (H_3PO_4). The flow rate was set at 0.5 mL min^{-1}, and the column temperature was maintained at 35°C. A 20 μL sample was injected for each analysis, and detection was performed at 254 nm. All treatments were analyzed in triplicate. Vitamin C concentration was calculated based on an external ascorbic acid standard calibration curve and expressed as μg mL^{-1}.

6. Total Phenolic Content: Total phenolic content was determined using a modified Folin–Ciocalteu method as described by Vinha et al. [29]. Samples were first centrifuged at 6000 rpm for 10 min using a Universal Centrifuge (Z326K, HERMLE Labortechnik GmbH, Germany). An aliquot of 50 μL of the supernatant was transferred into a test tube, followed by the addition of 125 μL of 10% (v/v) Folin–Ciocalteu reagent. After standing for 3 min, 50 μL of 7.5% (w/v) sodium carbonate (Na_2CO_3) solution was added. The mixture was incubated at room temperature for 120 min. Absorbance was measured at 725 nm using a microplate reader (Synergy™ HT Multi-Mode, BioTek Instruments Inc., USA). Each treatment was analyzed in triplicate. Total phenolic content was calculated from a gallic acid standard calibration curve and expressed as μg mL^{-1}.
7. Leaf Chlorophyll Content in Tomato Plants: Chlorophyll a and chlorophyll b contents were determined according to the method of Sonobe et al. [30], which allows simultaneous pigment determination in tomatoes. A 1 g sample of tomato tissue was placed in a tube, and 20 mL of acetone–hexane solution (4:6, v/v) was added. The mixture was vortexed for 10 min and centrifuged at 3000 rpm for 15 min. The supernatant was collected and filtered through Whatman No. 4 filter paper. Absorbance of the filtrate was measured simultaneously at 663 nm and 645 nm using a spectrophotometer. Chlorophyll a and b contents were calculated using the following Eqs. (4) and (5):

$$\text{Chlorophyll a (mg/100 mL)} = 0.999\ A663 - 0.0989\ A645 \tag{4}$$

$$\text{Chlorophyll b (mg/100 mL)} = -0.328\ A663\ + 1.77\ A645 \tag{5}$$

8. Statistical Analysis: Data were analyzed using one-way analysis of variance (ANOVA). Differences among treatment means were determined using Duncan's Multiple Range Test (DMRT) at the 5% significance level ($p < 0.05$).

3 Results and Discussion

3.1 Fresh Stem and Root Weigh

Fresh stem and root biomass was determined immediately after harvest to evaluate the influence of supplemental LED lighting on vegetative development (Fig. 5). Distinct differences were observed among treatments. Plants grown under the D200 treatment produced the greatest fresh biomass (1105.3 g $plant^{-1}$), followed by those receiving the C200 treatment (1036.5 g $plant^{-1}$), whereas the control plants recorded the lowest biomass (924.8 g $plant^{-1}$). These findings indicate that supplemental LED lighting substantially enhanced vegetative growth, particularly when a balanced light spectrum was combined with a higher photosynthetic photon flux density. The superior performance of the D200 treatment suggests that plant

biomass accumulation was influenced not only by light intensity but also by spectral composition. Although supplemental lighting was supplied exclusively during the evening (18:00–22:00 h), the additional photoperiod likely increased the cumulative daily light integral and prolonged photosynthetic carbon assimilation, thereby promoting greater biomass production [31]. Extending the effective photosynthetic period may also improve synchronization with endogenous physiological processes, resulting in more efficient allocation of assimilated carbohydrates to both shoots and roots. The beneficial effects of red and blue wavelengths have been extensively documented in greenhouse crop production. Red light primarily regulates stem elongation, leaf expansion, and biomass accumulation through phytochrome-mediated responses, whereas blue light contributes to chlorophyll biosynthesis, stomatal regulation, and improved photosynthetic efficiency [29,32]. Previous comparisons between LED systems and conventional high-pressure sodium (HPS) lamps demonstrated that red–blue LED illumination increased chlorophyll concentration and enhanced vegetative biomass more effectively than traditional lighting technologies [30]. These complementary physiological functions explain why combined red and blue spectra generally outperform monochromatic light treatments. In addition to spectral quality, the ratio between red and blue wavelengths strongly influences plant morphology and biomass partitioning. Earlier studies reported that a high proportion of red light (9:1) stimulated vegetative growth in cucumber [31], whereas a more balanced red-to-blue ratio (3:1) improved fresh and dry biomass accumulation in tomato by optimizing photosynthetic carbon fixation and assimilate distribution [32]. Likewise, an 8:2 red–blue combination has been associated with increased photosynthetic capacity and improved root growth [33]. Collectively, these studies suggest that balanced spectral combinations maximize biomass production by simultaneously promoting efficient light capture, carbon assimilation, and root development. Another factor contributing to the observed growth response was the positioning of the supplemental lighting system. In the present experiment, LED fixtures were installed approximately 30 cm above the canopy and inclined at 10°–15°, allowing more uniform light distribution throughout the crop canopy while minimizing mutual shading among plants. Improved light interception enhances canopy photosynthesis and supports more uniform biomass accumulation. Similar observations were reported by Yan et al. [34], who demonstrated that continuous red–blue LED exposure significantly increased both fresh and dry biomass in purple lettuce. Comparable responses have also been reported for *Codonopsis lanceolata*, where supplemental lighting stimulated stem thickening, root development, and total biomass production [35].

Overall, the present findings demonstrate that supplemental LED lighting effectively enhanced vegetative growth of greenhouse-grown cherry tomato under high-temperature conditions. The greatest biomass accumulation was achieved when an appropriate spectral combination was integrated with a relatively high light intensity, indicating that both light quality and quantity are essential determinants of plant productivity. In addition, fixture arrangement and lighting duration contributed to efficient canopy illumination, further supporting photosynthetic performance and biomass accumulation. It should be noted that the present study quantified fresh stem and root biomass as indicators of vegetative growth because these parameters directly reflect the plant response to supplemental lighting during early biomass accumulation. Other indicators of shoot performance, including plant height, leaf development, chlorophyll content, and fruit yield, were evaluated separately to provide a comprehensive assessment of above-ground growth. Although above-ground dry biomass was not measured, incorporating this parameter in future investigations would provide a more complete evaluation of biomass partitioning and improve understanding of the physiological responses of tomato plants to supplemental LED lighting.

The results indicate that supplemental LED lighting in red and blue wavelengths plays a critical role in enhancing tomato growth and development by increasing stem and root biomass, improving photosynthetic

efficiency, and promoting nutrient uptake. The application of red, blue supplemental lighting during periods of lower natural light availability, such as early evening, can effectively extend the photosynthetically active period of the plants. Optimizing the red-to-blue light ratio, such as 7:2 or 8:2, may further enhance vegetative growth and physiological performance.

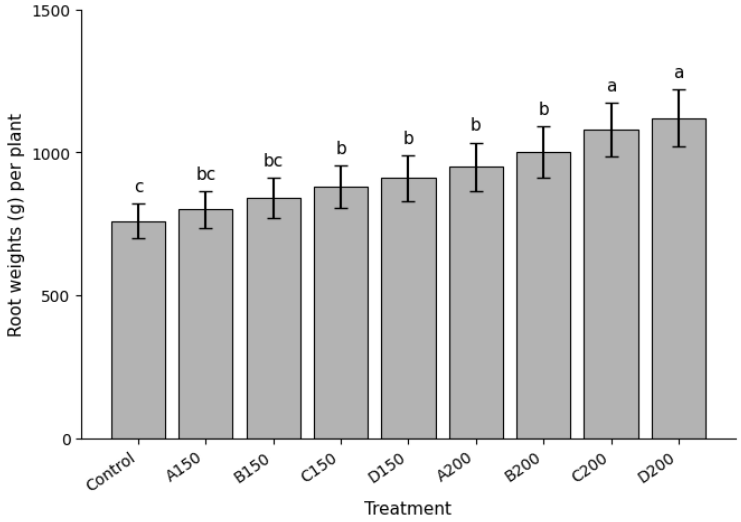


Figure 5: Plant and root weights (g) per plant in each treatment at the post-flowering stage. Values are expressed as mean ± SD. Different letters above bars indicate significant differences among treatments at $p < 0.05$ according to Duncan's multiple range test.

3.2 Yield Weight

Fruit yield, expressed as fresh fruit weight per plant, varied significantly among the supplemental lighting treatments (Fig. 6). The highest productivity was obtained from plants grown under the D200 treatment, which produced an average yield of 1228.5 g plant^{-1}, followed by C200 (1179.6 g plant^{-1}) and B200 (1164.6 g plant^{-1}). In contrast, the control plants cultivated without supplemental lighting exhibited the lowest yield, averaging 885.1 g plant^{-1}. These results clearly demonstrate that providing supplemental LED illumination at a photosynthetic photon flux density of 200 μmol m^{-2} s^{-1} substantially improved fruit production under greenhouse conditions, with the greatest response observed under the combined red–blue–white spectrum.

The increased yield observed in the high-intensity LED treatments is likely associated with improved photosynthetic performance and more efficient carbon assimilation. Supplemental lighting extends the effective photoperiod, enabling plants to continue photosynthetic activity after sunset and increasing the daily production of photoassimilates available for reproductive growth. Consequently, greater carbohydrate availability supports flower retention, fruit set, and subsequent fruit enlargement, ultimately resulting in higher marketable yield. Blue wavelengths contribute to this response by promoting stomatal opening through photoreceptor-mediated signaling pathways, thereby facilitating CO_2 diffusion into leaf tissues and improving transpiration efficiency [36]. Enhanced stomatal conductance increases the supply of CO_2 for photosynthetic carbon fixation, allowing plants to maintain higher photosynthetic rates under greenhouse conditions. At the same time, red wavelengths efficiently drive the photochemical reactions of photosynthesis, and when combined with blue light they provide complementary functions that optimize overall photosynthetic performance. Previous studies have shown that red–blue LED combinations stimulate the activity of ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), the key enzyme responsible for

carbon fixation in the Calvin cycle, thereby increasing carbohydrate production and biomass accumulation [37,38]. Compared with monochromatic lighting, mixed red–blue spectra consistently produce superior photosynthetic efficiency because both photosystems receive a more balanced spectral environment [39]. These physiological responses explain the higher fruit yield observed in the present study under combined spectral treatments. Another important factor is the duration of supplemental illumination. Earlier investigations demonstrated that applying red–blue LEDs for only 2–4 h during the evening increases chlorophyll *a*, chlorophyll *b*, and carotenoid concentrations, improving light-harvesting capacity and photosynthetic efficiency. Similarly, Wei et al. [40] reported that four hours of evening supplemental lighting significantly enhanced leaf photosynthesis in greenhouse-grown tomato. Increased pigment accumulation and enhanced RuBisCO activity improve carbon fixation efficiency, leading to greater synthesis of soluble carbohydrates that can be translocated from source leaves to developing fruits. Overall, the present findings indicate that the beneficial effects of supplemental LED lighting on tomato yield result from multiple complementary physiological mechanisms rather than increased light intensity alone. The integration of optimized spectral composition with an appropriate photon flux density prolonged photosynthetic activity, improved gas exchange, enhanced carbon assimilation, and promoted more efficient allocation of assimilates toward fruit production. Consequently, the D200 treatment produced the highest fruit yield, demonstrating that combining red, blue, and white LEDs at 200 μmol m^{-2} s^{-1} represents an effective strategy for improving greenhouse tomato productivity under tropical high-temperature conditions.

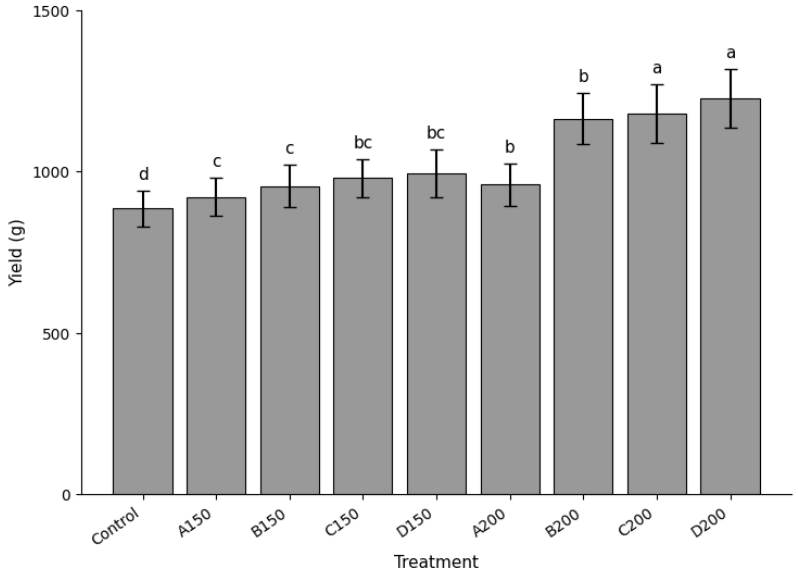


Figure 6: Yield weight (g) per plant in each treatment. Values are expressed as mean ± SD. Different lowercase letters above bars indicate significant differences among treatments ($p < 0.05$).

From the above analysis, it is shown that supplementary lighting from red and blue LEDs plays an important role in stimulating the growth and development of tomato plants, both in terms of yield weight and yield sweetness. Adjusting the ratio of red to blue light, such as 7:3 or 8:2, has shown the best results in stimulating plant growth (Fig. 7).

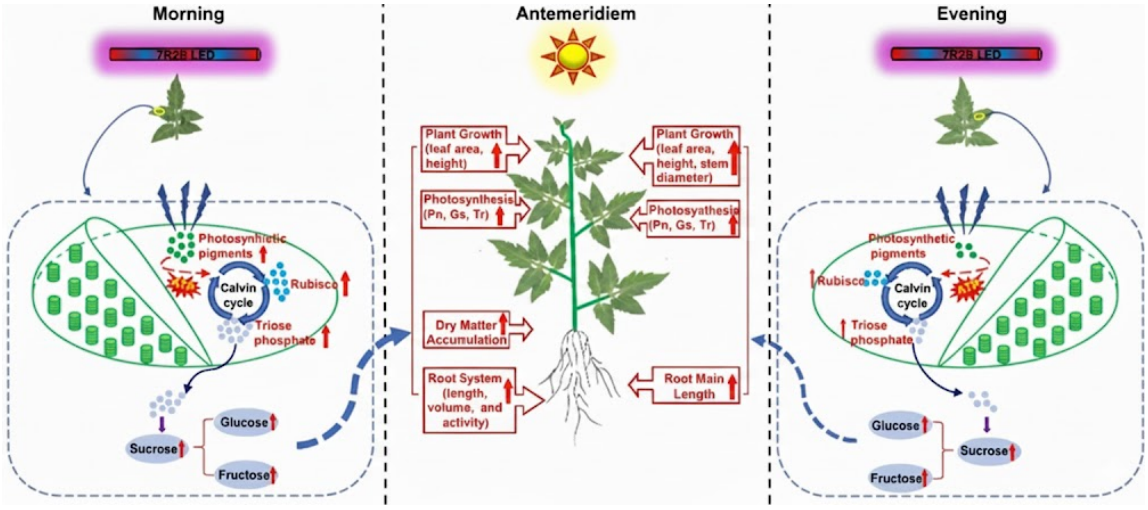


Figure 7: Tomato response to red and blue supplementary light.

3.3 Sweetness of Tomatoes

Fruit sweetness, expressed as total soluble solids (TSS; °Brix), was significantly influenced by supplemental LED lighting (Figs. 8 and 9). The control treatment produced the lowest TSS value (9.6°Brix), whereas the highest sweetness was observed in the C200 treatment (12.1°Brix). Similar improvements were obtained under the C150 and D200 treatments, both of which reached 12.0°Brix. These results demonstrate that supplemental lighting, particularly the combined red–blue spectrum supplied at 200 μmol m^{-2} s^{-1}, effectively enhanced sugar accumulation in tomato fruits under greenhouse conditions. The increase in soluble solids is closely associated with improved photosynthetic carbon assimilation under optimized spectral conditions. Extending the photoperiod with supplemental LEDs allows plants to maintain photosynthetic activity beyond natural daylight, resulting in greater production of photoassimilates that can subsequently be transported to developing fruits. Consequently, increased carbohydrate availability contributes directly to higher concentrations of soluble sugars and improved fruit sweetness. Blue light plays an important physiological role by stimulating stomatal opening through photoreceptor-mediated signaling, thereby facilitating CO_2 diffusion into leaf tissues and improving transpiration efficiency. Increased stomatal conductance enhances carbon fixation, while red light efficiently drives the photochemical reactions required for ATP and NADPH production. Together, these complementary functions improve the overall efficiency of photosynthesis and promote greater carbohydrate synthesis. Previous studies have reported that combined red–blue LED illumination increases the accumulation of glucose, fructose, sucrose, soluble sugars, and starch in tomato leaves and fruits, particularly when supplemental lighting is applied for 2–4 h during the evening [41]. Enhanced sugar accumulation has been associated with increased chlorophyll biosynthesis, improved pigment stability, and greater activity of Calvin cycle enzymes responsible for carbon fixation. As photosynthetic efficiency increases, a larger proportion of assimilated carbon is translocated from source leaves to sink organs, thereby increasing soluble solids in the fruit. This mechanism is particularly important under tropical summer conditions, where elevated temperatures frequently reduce photosynthetic efficiency and restrict carbohydrate accumulation. Although only a small proportion of incoming solar radiation is converted into chemical energy during photosynthesis, wavelengths within the photosynthetically active radiation (PAR) region (400–700 nm) are utilized with the greatest efficiency. Supplemental LEDs operating within this spectral range therefore provide an effective means of increasing light-use efficiency while compensating for the reduced natural radiation associated with daytime shade-net management. Similar

physiological responses have also been reported in other horticultural crops. For example, increased nighttime exposure to blue LED light enhanced anthocyanin biosynthesis and sugar accumulation in grape berries, demonstrating the important regulatory role of blue wavelengths in both pigment formation and carbohydrate metabolism [42]. Overall, the present findings indicate that the improvement in tomato sweetness resulted from the combined effects of optimized light quality and sufficient photon flux density. The balanced red–blue spectral combination, particularly at 200 μmol m^{-2} s^{-1}, enhanced photosynthetic carbon fixation, promoted efficient carbohydrate translocation to developing fruits, and increased soluble sugar accumulation. These physiological responses explain the significantly higher °Brix values observed under supplemental LED treatments compared with plants grown under natural light alone.

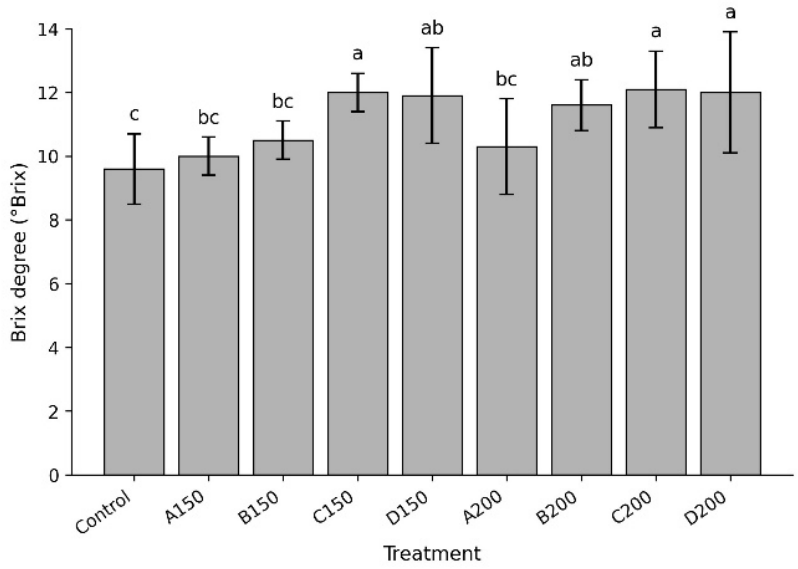


Figure 8: Sweetness (°Brix) per plant in each treatment. Values are expressed as mean ± SD. Different lowercase letters above bars indicate significant differences among treatments ($p < 0.05$).

From the above analysis, it is shown that supplementary lighting from red and blue LEDs plays an important role in stimulating the growth and development of tomatoes, both in terms of yield weight and yield sweetness. Adjusting the ratio of red to blue light, such as 3:2 or 3:1, has shown the best results in stimulating plant growth (Fig. 8).

Targeted red, blue LED supplementation applied during the evening periods enhances photosynthetic performance by stimulating chlorophyll biosynthesis and RuBisCO activity, thereby increasing Calvin cycle flux and triose phosphate production. The resulting rise in photoassimilate availability promotes sucrose synthesis and source–sink transport, leading to greater sugar accumulation in tomato fruits. Concurrently, improved carbon allocation supports root development and nutrient uptake, ultimately enhancing fruit yield and biochemical quality under greenhouse conditions.

3.4 Lycopene, Vitamin C, Total Phenolic, and Leaf Chlorophyll Content in Tomato Plants

Fig. 9 illustrates the effects of different light treatments on (A) lycopene content in tomato fruits, (B) vitamin C content in tomato fruits, (C) total phenolic content in tomato fruits, and (D) leaf chlorophyll content in tomato plants. Values are presented as mean ± SD, and different lowercase letters above the bars indicate statistically significant differences among treatments ($p < 0.05$). Lycopene content was higher in all supplemental-light treatments than in the control (Fig. 9A). The control exhibited an average

lycopene concentration of 29.8 μg mL^{-1}, whereas treatments receiving supplemental light at 150 and 200 μmol m^{-2} s^{-1} showed increased lycopene levels. The highest lycopene content was observed in the D200 treatment (38 μg mL^{-1}), which combined red and blue light at a 3:1 ratio with white light. These findings demonstrate the positive effect of supplemental LED lighting on lycopene accumulation in tomato fruits. Previous studies have similarly demonstrated beneficial effects of supplemental LED lighting on tomato growth, yield, and fruit quality under controlled and semi-closed greenhouse conditions [43,44]. More broadly, light spectral quality can influence photosynthetic performance and other physiological responses of plants grown under artificial lighting environments [45–47]. In tomato, red and blue light treatments have been associated with changes in fruit growth and nutrient accumulation [48], while supplemental LED lighting has also been reported to increase lycopene and lutein contents in tomato fruits [49]. These previous findings support the present results, particularly the greater lycopene accumulation observed under the combined red–blue–white D200 treatment. Overall, the results suggest that appropriately configured supplemental LED lighting can enhance crop productivity while improving selected biochemical quality attributes of tomato fruits.

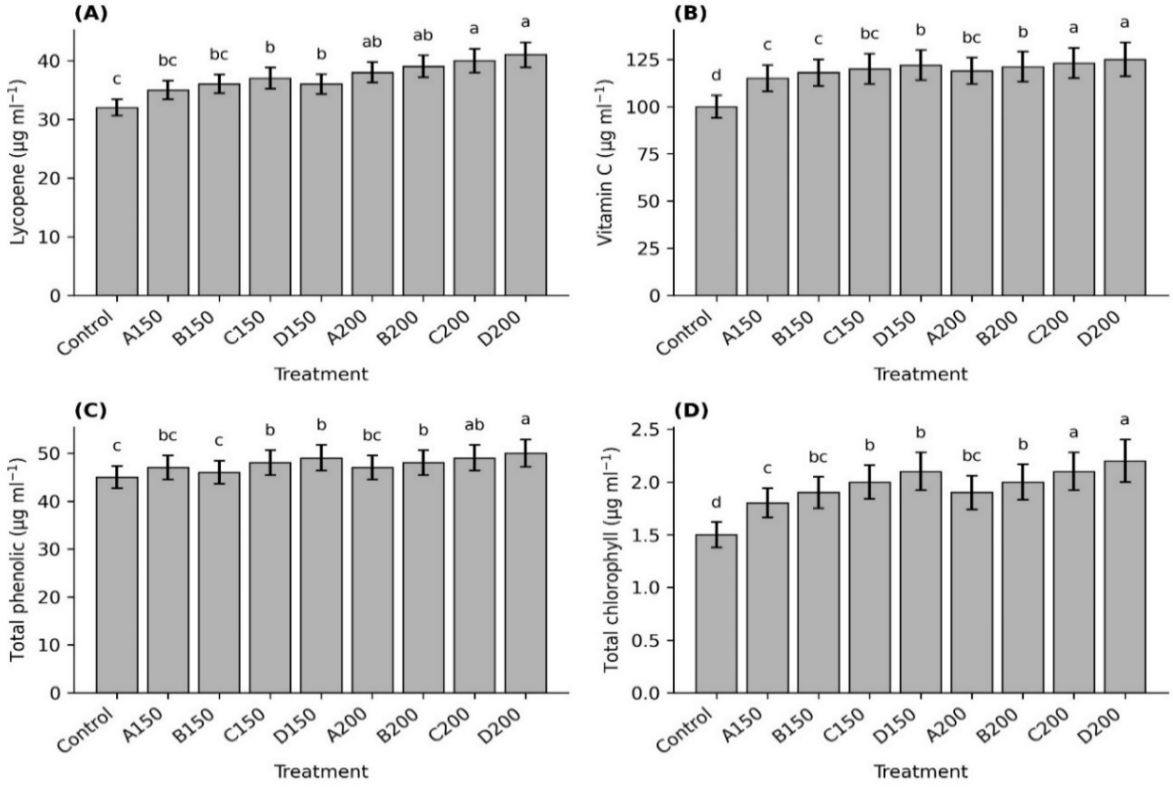


Figure 9: The effects of different light treatments on (**A**) lycopene, (**B**) vitamin C, and (**C**) total phenolic content in tomato fruits, and (**D**) leaf chlorophyll content in tomato plants. Values are expressed as mean ± SD. Different lowercase letters above bars indicate significant differences among treatments ($p < 0.05$).

Vitamin C (Fig. 9B). All treatments, including the control, exhibited vitamin C concentrations exceeding 100 μg mL^{-1}, with an overall mean of 121.5 μg mL^{-1}. The highest values were observed in the B200 and D200 treatments (128 μg mL^{-1}), although these were comparable to the control. Previous findings on the effect of supplemental lighting on vitamin C in cherry tomatoes have been inconsistent. Lu et al. [50] reported increases in vitamin C under supplemental lighting, whereas Palmitessa et al. [47] observed minimal changes.

Vitamin C accumulation is known to depend on light intensity, spectral quality, canopy light penetration, and greenhouse architecture [51,52], which may explain the limited variation observed among treatments in the present study. Total Phenolic Content (Fig. 9C). The control group exhibited the lowest total phenolic content (43 μg mL^{-1}). All treatments receiving supplemental light showed values exceeding 50 μg mL^{-1}, with the highest concentrations observed in D200 (55 μg mL^{-1}) and D150 (54 μg mL^{-1}). These findings are consistent with reports by Ouzounis et al. [53], who demonstrated that red and blue LED supplementation enhances phenolic compound accumulation in tomatoes, potentially through light-mediated regulation of secondary metabolism at the genetic level. Leaf chlorophyll content in tomato plants (Fig. 9D). The control treatment recorded the lowest leaf chlorophyll content (1.55 μg mL^{-1}), whereas D150 and D200 exhibited the highest values (2.0 μg mL^{-1}). Previous studies have shown that red and blue LED lighting improves light capture and CO_2 assimilation, thereby enhancing chlorophyll synthesis and photosynthetic capacity, which ultimately contributes to increased plant productivity. Evidence from other crops further supports these observations. For example, Kasideth et al. [54] demonstrated that combined white, red, and blue supplemental lighting improved antioxidant content and reduced weight loss in turmeric rhizomes. Similarly, Subsequent studies [55–57] reported increased phenolic accumulation in germinating wheat, lentils, radishes, and buckwheat sprouts under red and blue LED exposure. Several studies have also shown that supplemental lighting enhances photosynthetic performance and yield across horticultural crops. Joshi et al. [58] reported that red and blue LEDs increased the photosynthetic rate of inner canopy leaves by 3.5 times–5.7 times and improved pepper yield by 30%. Li et al. [59] observed enhanced stomatal conductance, carbon assimilation, and an 8.7% yield increase in tomatoes under LED supplementation. Lu et al. [50] further reported a positive linear relationship between tomato yield and duration of red, blue light exposure. Improvements in chlorophyll content and photosynthetic capacity under supplemental lighting have been widely documented [60,61]. Increased chlorophyll concentrations are typically associated with enhanced photosynthetic rates, particularly in developing leaves. However, studies have shown that although chlorophyll content may decline as leaves age, light absorption efficiency (ABS/CS) can remain relatively stable [61]. Tewolde et al. [62] also demonstrated that both HPS and LED supplemental lighting significantly increased chlorophyll content in the middle and lower canopy leaves of tomato plants. Overall, the present findings confirm that supplemental red and blue LED lighting not only enhances biochemical quality attributes, such as phenolic compounds and chlorophyll, but also supports photosynthetic efficiency, which contributes to improved fruit quality and yield under greenhouse conditions. One limitation of the present study is that the Daily Light Integral (DLI) was not continuously monitored throughout the experimental period. Consequently, the combined contribution of natural solar radiation and supplemental LED lighting could not be quantified. Future studies should incorporate continuous DLI measurements to better characterize the total light environment and further optimize supplemental lighting strategies under tropical greenhouse conditions.

4 Conclusions

The present study demonstrated that both the spectral composition and intensity of supplemental LED lighting played decisive roles in regulating tomato growth, productivity, and fruit quality under tropical greenhouse conditions. Evening illumination (18:00–22:00 h) using red, blue, red–blue, and red–blue–white (3000 K) LEDs at photon flux densities of 150 and 200 μmol m^{-2} s^{-1} consistently enhanced vegetative development compared with plants grown under natural light alone. Supplemental lighting increased fresh biomass, fruit production, and soluble solids, indicating that extending the daily light period effectively compensated for the reduction in natural radiation caused by daytime shade-net application. Among all

treatments, the D200 treatment produced the most favorable plant responses. The combination of red, blue, and white LEDs supplied at 200 μmol m^{-2} s^{-1} promoted greater canopy expansion, increased leaf area development, and higher chlorophyll *a*, chlorophyll *b*, and total chlorophyll concentrations than the other lighting regimes. These physiological improvements suggest that the balanced spectral composition enhanced light capture and photochemical efficiency, thereby increasing photosynthetic carbon assimilation throughout the cultivation period. Consequently, greater quantities of assimilated carbon became available for biomass production and reproductive development. Improved photosynthetic performance also influenced fruit biochemical composition. Once the carbon requirements for vegetative growth had been satisfied, surplus photoassimilates were redirected toward secondary metabolic pathways involved in the synthesis of nutritionally important compounds, including lycopene and phenolic constituents. This physiological response explains the simultaneous improvement in fruit yield and nutritional quality observed under supplemental LED treatments. Therefore, extending the photoperiod by four hours each evening represents an effective approach for maintaining photosynthetic activity during periods of limited daytime light availability while alleviating the negative effects of high-temperature stress during the Thai summer. From a practical perspective, integrating daytime shading with targeted evening LED supplementation provides an effective environmental management strategy for protected tomato cultivation in tropical climates. The combination reduces excessive heat during periods of intense solar radiation while restoring the daily light integral through controlled supplemental illumination, thereby maintaining plant productivity without exposing plants to prolonged thermal stress. This integrated approach may therefore provide greenhouse growers with a practical method for stabilizing production and improving fruit quality during the hottest months of the year. Although supplemental lighting inevitably increases electricity consumption, the associated operating costs may be compensated by improvements in marketable yield and fruit quality, particularly when energy-efficient LED fixtures are operated for a relatively short period each day. The lighting schedule adopted in the present study (18:00–22:00 h) offers a practical compromise between energy use and crop performance, making the technology more feasible for commercial greenhouse production and community-based agricultural enterprises. Nevertheless, further research should include a comprehensive techno-economic assessment incorporating installation expenses, electrical energy consumption, operational costs, and return on investment to determine the long-term economic viability of this production system under commercial cultivation conditions.

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Ethics Approval: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

ABS/CS	Absorption efficiency
DMRT	Duncan's multiple range test
GHG	Greenhouse gas
HPS	High-pressure sodium
LED	Light-emitting diode
PAR	Photosynthetically active radiation
PPFD	Photosynthetic photon flux density
RuBisCo	Ribulose-1,5-bisphosphate carboxylase/oxygenase
TSS	Total soluble solids
TTA	Titratable acidity

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