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Effect of Supplemental Light Quality and Season on Growth and Photosynthesis of Two Cultivars of Greenhouse Sweet Pepper (*Capsicum annuum* L.)

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ABSTRACT

In the past decade, light-emitting diodes (LEDs) have been increasingly regarded as a suitable replacement for many other types of light source. They have attracted lots of attention. Supplemental lighting improves growth and yield of greenhouse vegetables such as sweet pepper, cucumber and tomato all-year round. In the present study, the growth and photosynthetic functionality of two greenhouse sweet pepper cultivars, i.e. 'Padra' and 'Shadleen', were evaluated in response to the quality of LED lighting on sweet pepper seedlings. For this purpose, three combinations of red (R) and blue (B) LEDs (R90B10, R80B20, and R70B30 were used, with a light intensity of 200 μmol m-2 s-1 in all LED light treatments. Evaluations were done in two growing seasons, winter and summer, in Rasht, Iran. Seedlings exposed to supplemental light had thicker stems, wider leaf area, higher biomass, and greater photosynthetic functionality. We observed an increase in the ratio of B-light LED to the positive effects on the growth and photosynthesis functionality of the seedlings. However, no significant difference was observed between the cultivars. The effect of supplemental light was more emphasized in the winter. Thus, the control seedlings were weak and pale, while strong seedlings with dark green leaves were produced under the supplemental light. In conclusion, supplemental LED lighting appeared as a practical tool for the commercial production of greenhouse seedlings.

Abbreviations

Blue LED (B), Chlorophyll Fluorescence Parameter (CFP), Chlorophyll (Chl), Daily Light Integrals (DLI), High-Pressure Sodium lamps (HPS), Leaf Area (LA), Leaf Dry Weight (LDW), Light-Emitting Diodes (LEDs), Leaf Fresh Weight (LFW), Leaf Number (LN), Red LED (R), Root Dry Weight (RDW), Root Fresh Weight (RFW), Relative Humidity (RH), Stem Diameter (SD), Stem Dry Weight (SDW), Stem Fresh Weight (SFW), Stem Height (SH), Supplemental Lighting (SL), Specific Leaf Area (SLA), Total Dry Weight (TDW), Total Fresh Weight (TFW).

Introduction

Vegetables, flowers and fruits are major crops produced in greenhouses. The development of greenhouse cultivation has led to high levels of production per unit area and improved crop quality. In practice, greenhouses significantly increase annual crop yields by shortening the cultivation duration and increasing the number of crop cycles (Grechkina et al., 2016; Yano and Cossu, 2019). Proper planning for the

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establishment of a functional greenhouse production system requires overcoming the limitations that prevent the optimum output of this type of cultivation.

Light is one of the most important environmental factors affecting plant growth, responses and productivity (Li et al., 2016). Using modern greenhouse technologies make it possible to increase plant density and utilize the vertical profile of a greenhouse, compared to open field cultivation. However, a major challenge is associated with poor light exposure and cross-shading (De Pascale et al., 2012; Jiang et al., 2017). Seasonality of light is a common challenge for greenhouse production, especially in high latitudes and areas with cloudy periods. On a cloudy day, an insufficient light intensity and a short duration of lighting may impose limitations on photosynthesis (Esmaili et al., 2022; Javadi Asayesh et al., 2021; Wang et al., 2012), poor fruit set, slow fruit growth, and postponed fruit coloring (Lee et al., 2014), resulting in the reduction in the efficiency of agricultural production (Wang et al., 2012). Therefore, in light-limited climates, supplemental lighting (SL) is used to overcome those limitations (Gómez and Mitchell, 2013; Javadi Asayesh et al., 2021).

Artificial light sources are often used to supplement the limited solar radiation received by a greenhouse crop. Even though high-pressure sodium lamps (HPS) are the most common artificial source of light used in greenhouses, these lamps do not have high efficiency due to high cost of energy. They emit large amounts of heat and are difficult to modify in their spectrum (Klamkowski et al., 2014). Furthermore, the outer bulb temperature of the HPS lamps reaches up to 450 °C, and this requires an increase in the distance between lamps and plants, which reduces the light efficiency (Toyoki Kozai, 2016). Light-emitting diodes (LED) are an appropriate alternative to conventional light sources due to very high energy efficiency, minimal heat emission and ease of spectrum manipulation. In the long-run, initial and operational costs for LED illumination may be lower than traditional lighting (Lastochkina et al., 2022; Mitchell et al., 2012; Moosavi-Nezhad et al., 2022; Singh et al., 2015; Turanov et al., 2016).

The chemical, morphological, and photosynthetic reactions of the plant depend on the intensity and quality of the lighting environment (Ashrostaghi et al., 2022; Esmaili et al., 2021a, b; Seif et al., 2021). Using LED lamps has its advantages. They can be adjusted to the spectrum and intensity of LED modules required for the optimization of plant growth and productivity (Lee et al., 2014; Singh et al., 2015). Portable and compact in size, long functional life, low operating temperature, wavelength specificity, and linear photon output with electrical input current make LEDs ideal for use as supplemental lighting systems for greenhouse crops (Massa et al., 2008). However, before being introduced to the commercial greenhouse market, it is necessary to examine LEDs in terms of spectral quality required for plant growth (Grechkina et al., 2016).

Based on the available literature, R and B lights are the main spectra for induction of photosynthesis, plant growth, and productivity in controlled environmental conditions (Ghorbanzadeh 2020; Hosseinzadeh 2021; Lastochkina et al., 2022). Therefore, in this study, the effect of supplemental LED lighting based on different combinations of R and B lights was studied on the photosynthesis and growth of two sweet pepper cultivars (*Capsicum annuum* L.) in greenhouse conditions.

Material and Methods

Location

Experiments were performed in the Research Greenhouse, Faculty of Agricultural Sciences, University of Guilan, Rasht, Iran (Latitude 37 degrees 16 minutes N; Longitude 49 degrees 36 minutes E; 7 meters above sea level) during the growing season (S1, planting date: 1 December 2018; the duration of light treatment: from 19 December 2018 to 20 January 2019; S2, planting date: 6 August 2019; the duration of light treatment: from 23 August 2019 to 23 September 2019). Mean outdoor daily light integrals (DLIs) in Rasht were 14 mol m^{-2} d^{-1} at S1, compared to 25 mol m^{-2} d^{-1} at S2 (obtained from the Rasht agricultural meteorological station), and the average indoor DLI was 8.4 mol m^{-2} d^{-1} and 15 mol m^{-2} d^{-1}, respectively (recorded with a Skye Instruments Ltd, SKP 200 photometer).

Plant materials

The experiment was conducted as a split plot in the form of a completely randomized design. Seeds of two sweet pepper cultivars (*Capsicum annum* L.), including red ('Padra') and yellow ('Shadleen') were provided from Meridiem seeds. Co, Iran and planted (1.5 times more than required seedling) at the depth of 0.5 cm in 4 × 4 × 8 cm transplant trays containing a mixture of cocopeat and perlite. In the cotyledon stage, from the existing seedlings, 96 healthy, strong, matched, and uniform-sized plants were selected and transferred to 1 L plastic pots (10 × 12 × 12 cm). The pots were randomly placed under 4 LED light treatments. Each treatment included 24 plants and lasted for 30 days. Irrigation was done with Hoagland nutrient solution during the growing season, according to the needs of the plants. During the 30-days treatment period, the relative humidity (RH) was maintained at 75%, with a 14 h photoperiod (5 am–7 pm) and a temperature of 25 °C during the day and 18-20 °C at night. The first measurements were made two weeks after the start of light treatment, when most treated plants had 4-6 leaves, and the second measurements were carried out one month after supplemental light application, concurrently with the beginning of flowering.

Lighting treatments

LED modules (36W, Iran Grow Light Co, Iran) were placed in 20 cm above the seedling (Fig. 1). The peak wavelength of the red LED light was 660 nm, and the peak wavelength of the blue LED was 460 nm. According to the literature (Hikosaka et al., 2013; Naznin et al., 2019), the light intensity for all LED light treatments was maintained at 200 μmol m^{-2} s^{-1} throughout the experiment (measured with a Skye Instruments Ltd, SKP 200 photometer). The photoperiod was 14 h (5 am- 7 pm) and supplemental lights were turned off when the incident solar radiation was above 400 μmol m^{-2} s^{-1} (Guo et al., 2016; Maureira et al., 2022). There were a total of 4 treatments (Table 1) with 3 replicates and 24 plants per replication. Light diffusion was prevented from occurring among the treatments.

Fig 1. Sweet pepper seedlings exposed to supplemental light with different spectral combinations of red and blue light

Table 1. Lighting treatments based on red (R) and blue (B) spectra and the contribution of each light power LEDs in the overall light composition.

Treatment	Description
T1	R : B (90% : 10%; 9: 1)
T2	R : B (80% : 20%; 8: 2)
T3	R : B (70% : 30%; 7: 3)
CK	Control (without supplemental light)

Peak wavelengt λp was 660 nm for red LED and 430 nm for blue LED.

Analysis of growth parameters

At the end of the experiment, by removing the seedlings from the pots, we detached the roots, stems and leaves from the plants and measured the stem height (SH), stem diameter (SD), leaf number (LN) and leaf area (LA) in all treatment groups. Then, three plants were randomly selected from each treatment to measure parameters such as root fresh weight (RFW), stem fresh weight (SFW), leaf fresh weight (LFW), and total fresh weight (TFW). To reach a constant mass and determine the dry weight, samples were placed in separate bags and dried in an oven at 75 °C for 48 hours, followed by measurements of root dry weight (RDW), stem dry weight (SDW), leaf dry weight (LDW), and total dry weight (TDW). Finally, specific leaf area (SLA) and health index were evaluated.

The health index of selected plants was determined using the equation 1 (Fan et al., 2013):

$$\textbf{Health index} = \frac{\text{Stem diameter}}{\text{Stem height}}\textbf{Dry weight}$$

equation 1

where the stem diameter was measured by vernier calipers at the internode above the cotyledons, the stem height was measured by a ruler from the main stem base to the top of the young plants, and dry weight was measured using an electronic balance.
The SLA (cm² g⁻¹) of each selected plant was measured using the equation 2 (Ziaf et al., 2009):

$$\mathbf{SLA} = \frac{\textbf{Leaf area}}{\textbf{Leaf dry weight}} \quad \text{equation 2}$$

where, leaf area was determined by leaf area meter (model A3 Light box G.C.L Bubble Etch Tanks) and leaf dry weight was measured using an electronic balance.

Analysis of chlorophyll measurement

Chlorophyll Fluorescence Parameter (CFP) was measured using a portable chlorophyll fluorometer (Mini-Pulse-AmplitudeModulation 2000, Walz, Germany). The youngest fully-developed leaves were placed in the dark using leaf-clip holders and were treated to oxidaize the photosystem II reaction center. After a 30-minute dark adaptation, the parameters were recorded.
The maximum efficiency of photosystem II was measured using equation 3 (ALKahtani et al., 2020).

$$\textbf{Maximum quantum efficiency of PSII} = \frac{F_v}{F_m} = \frac{(F_m - F_0)}{F_m} \quad \text{equation 3}$$

where F0 is the minimum chlorophyll fluorescence (measured using a measuring beam of <0.1 μmol m^{-2} s^{-1}), F_m is the maximum fluorescence (determined after a 1 s saturating pulse of >3500 μmol m^{-2} s^{-1}), F_v is the variable fluorescence (determined by the difference between F_m and F_0), and F_v/F_m is the maximum quantum yield of PSII photochemistry in dark-adapted cells.

Determination of chlorophyll a, b and total contents

Fresh leaf tissues (0.05 g) were crushed by a ceramic mortar. The extraction was done using 10 mL of 80% acetone. The extract was filtered through Watmann No. 1 filter paper, 0.45 μm. Extraction was performed several times until the plant tissues became completely colorless. The absorbance of the final concentrated extract (20 ml) was measured using a UV- visible spectrophotometer at 663.2 nm and 646.8 nm. Chlorophyll (a, b and total) contents were calculated according to the following equations (Ranganna, 1997):

$$\boldsymbol{Chl.a\ (mg\ ml^{-1}) = (12.25 \times OD_{663.2}) - (2.79 \times OD_{646.8})} \quad \text{equation 4}$$

$$\boldsymbol{Chl.b\ (mg\ ml^{-1}) = (21.50 \times OD_{646.8}) - (5.10 \times OD_{663.2})} \quad \text{equation 5}$$

$$\boldsymbol{Chl.total\ (mg\ ml^{-1}) = (18.71 \times OD_{646.8}) + (7.15 \times OD_{663.2})} \quad \text{equation 6}$$

Where $OD_{663.2}$ and $OD_{646.8}$ are optical absorption values read by the device at 663.2 nm and 646.8 nm, respectively. Chlorophyll a, chlorophyll b, and total chlorophyll were measured in mg per 100 g of fresh weight (mg g^{-1} FW).

Statistical analyses

The normality test (skewness and kurtosis) was carried out in the range of -2 to 2, using Statistical Product and Service Solutions for Windows, version 16.0 (SPSS Inc., Japan). Levene's test of variance homogeneity considered the season treatment and revealed an absence of significance, so a combined analysis was performed. Analysis of variance (Statistical Analysis Software, version 9.1, SAS Institute Inc, Cary, NC, USA) was run on growth and photosynthesis parameters to evaluate whether they have a significant relationship with light, season, pepper cultivars, and also with interactive effects of light × season, season × cultivar, light × cultivar, and light × season × cultivar. The differences between the mean values were tested using Tukey's multiple comparison test ($P < 0.01$ and $P < 0.05$).

Results

Growth parameters

The results of variance analysis indicated that the growth parameters correlated strongly with light treatments and they were strongly season-dependent ($P<0.01$) (Table 2). For most of the growth parameters, the interactive effect of season × light was also significant at 1%. While the individual effect of cultivar as well as the interactive effects of light × cultivar and season × cultivar were not statistically significant (Table 3).

Table 2. The normality test for growth parameters of sweet pepper seedlings exposed to different quality of supplemental light.

Normalization test	Growth Parameters													
	LN	LA (cm^2)	LFW (g)	LDW (g)	SLA (cm^2 g^{-1})	SH (cm)	SD (mm)	SFW (g)	SDW (g)	Health Index	RFW (g)	RDW (g)	TFW (g)	TDW (g)
Skewness	-0.416	-0.375	-0.618	-0.426	1.640	0.714	0.108	0.189	0.421	0.645	0.016	0.392	-.063	0.161
Kurtosis	-0.571	-0.566	-0.483	-0.804	1.951	-0.194	-1.862	-1.407	-1.380	-1.278	-1.080	-1.092	-1.089	-1.281

Abbreviations: LA: Leaf Area, LDW: Leaf Dry Weight, LFW: Leaf Fresh Weight, LN: Leaf Number, RDW: Root Dry Weight, RFW: Root Fresh Weight, SD: Stem Diameter, SDW: Stem Dry Weight, SFW: Stem Fresh Weight, SH: Stem Height, SLA: Specific Leaf Area, TDW: Total Dry Weight, TFW: Total Fresh Weight.

Table 3. Variance analysis for growth parameters of sweet pepper seedlings exposed to different quality of supplemental light.

Source	Df	Mean Square (MS)													
		LN	LA (cm^2)	LFW (g)	LDW (g)	SLA (cm^2 g^{-1})	SH (cm)	SD (mm)	SFW (g)	SDW (g)	health index	RFW (g)	RDW (g)	TFW (g)	TDW (g)
Season	1	157.7**	454352**	130**	1.92**	50805**	1406**	178**	405.7**	5.80**	0.513**	408**	5.43**	2676**	37.28**
Season Error	4	0.5	352.8	0.33	0.009	403	1.14	0.03	0.36	0.012	0.002	0.96	0.003	1.95	0.02
Light	3	100.2**	53498**	104.3**	1.64**	157806**	29.35**	3.32**	26.8**	0.52**	0.051**	309**	2.05**	1080**	11.62**
Light × season	3	0.62^{ns}	3748^{ns}	0.33^{ns}	0.02*	19013**	118.8**	0.48**	1.21^{ns}	0.097**	0.027**	31.9**	0.32**	47**	0.97**
Light × season Error	12	0.67	1692	0.49	0.03	1228	0.59	0.037	0.41	0.011	0.001	1.63	0.02	3.31	0.06
Cultivar	1	2.52^{ns}	469^{ns}	0.02^{ns}	0.001^{ns}	386^{ns}	7.17^{ns}	0.05^{ns}	0.35^{ns}	0.01^{ns}	0.002^{ns}	0.087^{ns}	0.01^{ns}	1.14^{ns}	0.04^{ns}
Season × Cultivar	1	0.02^{ns}	588^{ns}	1.87^{ns}	0.01^{ns}	510^{ns}	3.97^{ns}	0.02^{ns}	0.1^{ns}	0.003^{ns}	0.001^{ns}	0.025^{ns}	0.01^{ns}	0.80^{ns}	0.002^{ns}
Light × Cultivar	3	0.69^{ns}	317^{ns}	0.42^{ns}	0.006^{ns}	807^{ns}	2.35^{ns}	0.04^{ns}	0.46^{ns}	0.01^{ns}	0.001^{ns}	0.89^{ns}	0.003^{ns}	3.83^{ns}	0.06^{ns}
Season × Light × Cultivar	3	0.85^{ns}	222^{ns}	0.199^{ns}	0.85^{ns}	194^{ns}	3.74^{ns}	0.02^{ns}	0.38^{ns}	0.004^{ns}	0.001^{ns}	0.72^{ns}	0.001^{ns}	1.28^{ns}	0.005^{ns}
Residual Error		0.70	879	0.38	0.01	3102	1.51	0.02	0.58	0.009	0.001	0.987	0.021	2.43	0.05
Coefficient of variation	-	6.44	7.99	6.29	9.72	14.13	6.94	3.8	11.85	15.11	21.01	9.76	17.60	5.91	8.99

^{ns}, *, **: Non significant and significant at 5% and 1% probability level, respectively.

Abbreviations: LA: Leaf Area, LDW: Leaf Dry Weight, LFW: Leaf Fresh Weight, LN: Leaf Number, RDW: Root Dry Weight, RFW: Root Fresh Weight, SD: Stem Diameter, SDW: Stem Dry Weight, SFW: Stem Fresh Weight, SH: Stem Height, SLA: Specific Leaf Area, TDW: Total Dry Weight, TFW: Total Fresh Weight.

As shown in Table 3, the interactive effect of season × light was not significant on leaf count, leaf area, leaf fresh weight, and stem fresh weight. Thus, the individual effect of light and the individual effect of the season on the mean values of these parameters were separately documented (Tables 4 and 5). The data in Table 4 showed the mean value of each parameter in the total of two growing seasons under different light treatments. Data in Table 5 showed the mean value of each parameter in all plants in each growing season.
Differences between the mean values using Tukey's test showed that the leaf count, leaf area, leaf fresh weight, and stem fresh weight of the young sweet pepper plants were significantly different under all levels of supplemental light ($p<0.01$), compared to the condition without supplemental light (control sample). No statistically significant differences were observed between T1, T2, and T3 plants (Table 4). Also, the S2 growing period caused a significant increase in the leaf count, leaf area, leaf fresh weight, and stem fresh weight of young sweet pepper plants, compared to the S1 growing period, which can be attributed to the difference in natural daily light integral at S2 and S1 (Table 5).

Table 4. Individual effect of supplementary light with different spectra of red and blue light (refer to Table 1) on the mean values of some growth parameters of sweet pepper.

Light treatment	Growth parameters			
	LN	LA (cm^2)	LFW (g)	SFW (g)
T1	14.92[a]	411.92[a]	11.33[a]	7.21[a]
T2	14.25[a]	403.00[a]	11.04[a]	6.94[a]
T3	14.33[a]	399.17[a]	11.49[a]	7.13[a]
CK	8.75[b]	271.67[b]	5.40[b]	4.11[b]

Data are shown as treatment average of three replicates; mean values followed by different letters in the same column indicate significant differences by Tukey's test ($p\leq0.01$).

Table 5. Individual effect of season on mean values of some growth parameters of sweet pepper seedlings exposed to different spectra of supplemental light.

Season	Growth Parameters			
	LN	LA (cm^2)	LFW (g)	SFW (g)
S1	270	6579	196.1	82.55
S2	357	11249	275.1	222.11

Data are shown as treatment average of three replicates.

S1: The average indoor DLI < 10 mol m^2 d^{-1} (range of 8-9 mol m^2 d^{-1})

S2: The average indoor DLI > 10 mol m^2 d^{-1} (range of 14-16 mol m^2 d^{-1})

Analysis of variance on growth parameters confirmed a significant relationship between interactive effects of light × season and some growth parameters (LDW, SLA, SH, SD, SDW, health index, RFW, RDW, TFW, and TDW. See Table 3). Thus, the interactive effect of season × light on the means of these parameters was evaluated (Table 6). Investigating the differences between the means using Tukey's multiple comparison test at the 1% level showed that all levels of supplementary artificial light significantly increased leaf dry weight, stem diameter, stem dry weight, root fresh weight, root dry weight, health index, total fresh weight, and total dry weight, compared to the control treatment. However, there was no statistical difference among T1, T2, and T3 plants.
As shown in Table 6, differences between the means of leaf dry weight, stem diameter, stem dry weight, root fresh weight, root dry weight, health index, total fresh weight, and total dry weight at S2 were significantly higher than the S1, especially in the control treatment ($p<0.01$). For example, the stem dry weight showed a 2.2-fold increase at S2, compared to S1 in all supplemental light levels, and this increase became 3.9-fold, compared to the control treatment.
In the case of SLA, all levels of supplementary artificial light showed a significant decrease in SLA, compared to the control treatment (Table 6). As shown in Table 6, the difference between the mean values of SLA at S2 was significantly higher

than those at S1 ($p<0.01$). This difference was particularly pronounced in the control treatment, which increased by 50%.

Differences between the mean values of stem height at S1 at all levels of supplementary artificial light were significantly higher than the control treatment ($p<0.01$). At S2, however, taller stems were observed in the control treatment. In addition, studying the differences between the mean values of stem height at S2 ($p<0.05$) showed a significant difference among T1, T2, and T3 plants. Specifically, T3 (30% blue light) had the shortest stem.

Table 6. Interactive effect of season × light on mean values of some growth parameters of sweet pepper seedlings exposed to different quality of supplemental light (refer to Table 1).

Growth Parameters	season	Light Treatment				F value	Pr
		T1	T2	T3	CK		
LDW (g)	S1	0.99 ^{a}	0.92 ^{a}	1.02 ^{a}	0.32 ^{b}	122.86	0.0001
	S2	1.44 ^{a}	1.40 ^{a}	1.41 ^{a}	0.61 ^{b}	70.61	0.0001
SLA (cm^2 g^{-1})	S1	318 ^{b}	343 ^{b}	310 ^{b}	474 ^{a}	17.14	0.0008
	S2	356 ^{b}	349 ^{b}	344 ^{b}	657 ^{a}	34.11	0.0001
SH (cm)	S1	16.47 ^{a}	16.27 ^{a}	15.93 ^{a}	12.73 ^{b}	171.22	0.0001
	S2	24.70 ^{b}	24.08 ^{bc}	22.65 ^{c}	32.97 ^{a}	44.37	0.0001
SD (mm)	S1	2.34 ^{a}	2.23 ^{a}	2.35 ^{a}	1.64 ^{b}	79.40	0.0001
	S2	6.21 ^{a}	6.32 ^{a}	6.51 ^{a}	4.93 ^{b}	78.96	0.0001
SDW (g)	S1	0.35 ^{a}	0.31 ^{a}	0.37 ^{a}	0.11 ^{b}	68.19	0.0001
	S2	1.15 ^{a}	1.11 ^{a}	1.13 ^{a}	0.53 ^{b}	31.24	0.0001
health index	S1	0.050 ^{a}	0.043 ^{a}	0.055 ^{a}	0.014 ^{b}	60.90	0.0001
	S2	0.292 ^{a}	0.293 ^{a}	0.324 ^{a}	0.080 ^{b}	42.12	0.0001
RFW (g)	S1	9.27 ^{a}	8.54 ^{a}	9.50 ^{a}	1.74 ^{b}	407.82	0.0001
	S2	14.35 ^{a}	18.04 ^{a}	16.49 ^{a}	3.51 ^{b}	146.09	0.0001
RDW (g)	S1	0.64 ^{a}	0.59 ^{a}	0.64 ^{a}	0.09 ^{b}	306.49	0.0001
	S2	1.24 ^{a}	1.57 ^{a}	1.51 ^{a}	0.34 ^{b}	47.56	0.0001
TFW (g)	S1	23.08 ^{a}	21.55 ^{a}	23.65 ^{a}	7.21 ^{b}	319.27	0.0001
	S2	37.62 ^{a}	40.98 ^{a}	39.58 ^{a}	17.05 ^{b}	205.22	0.0001
TDW (g)	S1	1.98 ^{a}	1.83 ^{a}	2.05 ^{a}	0.53 ^{b}	211.43	0.0001
	S2	3.82 ^{a}	4.08 ^{a}	4.06 ^{a}	1.48 ^{b}	111.83	0.0001

Data are shown as average values of three replicates. Mean values followed by different letters in the same entry indicate significant differences by Tukey's ($p\leq0.01$) ($p\leq 0.05$). S1: The average indoor DLI < 10 mol m^2 d^{-1} (range of 8-9 mol m^2 d^{-1}). S2: The average indoor DLI > 10 mol m^2 d^{-1} (range of 14-16 mol m^2 d^{-1})

Chlorophyll measurement

A study of the normal distribution of measured data based on skewness and kurtosis tests showed that all data had a normal distribution (Table 7).

Chlorophyll fluorescence parameter

Chlorophyll fluorescence parameters correlated strongly to light treatments and were strongly season-dependent ($p<0.01$). While the individual effects of cultivar treatment and the interactive effects of light × cultivar and season × cultivar were not statistically significant (Table 8), the analysis of variance on chlorophyll fluorescence parameters confirmed a significant relationship between the interactive effects of light × season and most chlorophyll fluorescence parameters (Fm, Fv, and Fv/Fm) (Table 8). Thus, the interactive effect of season × light on the mean values of these parameters was evaluated (Table 9).

In evaluating the differences between the mean values using Tukey's multiple comparison test ($p<0.01$), it was found that all levels of supplementary artificial light significantly increased chlorophyll fluorescence parameters compared to the control treatment. As shown in Table 9, differences between the means of chlorophyll fluorescence parameters at S2 were significantly higher than those at S1, especially in the control treatment ($p<0.01$).

Chlorophyll a, b, and total contents

Chlorophyll a, chlorophyll b, total chlorophyll and Chl. a/ Chl. b correlated strongly with the light treatments. Furthermore, chlorophyll a, chlorophyll b, and total chlorophyll were strongly season-dependent ($p<0.01$). However, the individual effects of cultivar treatments and interactive effects of light × cultivar and season × cultivar were not statistically significant (Table 8).

As shown in Table 8, the interactive effect of season × light was not significant on chlorophyll a, chlorophyll b, total chlorophyll, and Chl. a/Chl. b. Therefore, the individual effects of light and the individual effects of season on the mean values of these parameters were separately evaluated (Tables 10 and 11). The data in Table 10 show the mean values of each parameter in both growing seasons under different light treatments. The data in Table 11 shows the mean values of each parameter in all plants in each growing season.

Through Tukey's test, it was observed that chlorophyll a, chlorophyll b, total chlorophyll, and chlorophyll a/chlorophyll b under all levels of supplemental light were significantly different ($p<0.01$) compared to treatment without supplemental light (control sample), while there was no statistical difference among T1, T2, and T3 plants (Table 10). Also, the S2 growing period caused a significant increase in chlorophyll a, chlorophyll b and total chlorophyll, compared to the S1 growing period, although there was no statistical difference between S1 and S2 for Chl. a/ Chl. b (Table 11).

Discussion

Light quality has a considerable effect on the physiological processes and growth of plants through various photoreceptors (Bian et al., 2015; Ward et al., 2005). A lack of proper light can cause reductions in photosynthetic efficiency, thereby retarding plant growth (Aliniaeifard and Van Meeteren, 2017; Esmaili et al., 2020; Sobczak et al., 2021). Gomez and Mitchell (Gómez and Mitchell, 2013) compared high-pressure sodium lamps (OH-HPS) with intracanopy light-emitting diode (IC-LED, 95% red + 5% blue) for high-wire greenhouse tomato (*Solanum lycopersicum* L.) production in a northern climate (40 °N. latitude, West Lafayette, IN, USA). Although equivalent increases in fruit yield (weight and number) were achieved for either SL treatment compared to the unsupplemented control, the results of this study indicated significant energy savings using IC-LED SL compared to standard OH-HPS treatments.

Supplemental interlighting can improve light distribution within the crop canopy and lead to an increase in crop performance and light efficiency. Narrow rows in a twin-row greenhouse vegetable cultivation system may pose limitations on the applicability of HPS (with high bulb temperatures) as inter-lighting. Hao et al. (2012) investigated the fruit yield of greenhouse mini-cucumber using LEDs with different spectra as interlighting. Improvement in visual fruit quality and its effect on plant growth were reported (Hao et al., 2012). Li et al. (Li et al., 2016) used two LED lighting sets with R:B ratios of 6:3 (LED-A) and 8:1 (LED-B) as artificial light sources to explore the effects of supplementary lighting at night (2, 4, and 6 h) on pepper plants grown in a greenhouse without heating. The results of this study showed that plants grown under the LED-A1 strategy (R:B ratios of 6:3, lighting duration: 6 h) had significantly higher fresh weight and dry mass of fruits compared to the control, so that the yield of fresh fruit increased by more than threefold compared to the control.

In northern temperate climates with limited seasonal light, electric energy accounts for 10-30 percent of total production costs. Up to 60% of that is electricity used for supplemental light (Dyer et al., 2011; Gómez and Mitchell, 2013). In the northern regions of Iran, light limitation in cold seasons has made it necessary to apply supplemental light in greenhouses to keep normal yield performance in greenhouses.

The results obtained from the stem height data in the present study showed that the differences between the means of stem height at S1 at each level of supplementary artificial light were significantly higher than the control treatment, while at S2, the higher stem height was attributed to the control treatment. Sweet pepper usually requires a DLI of at least 12 mol m^2 d^{-1} (Bian et al., 2015; Ward et al., 2005), and the positive increasing trend continues in growth parameters up to a DLI greater than 40 mol m^2 d^{-1} (Sobczak et al., 2021). At S2, the DLI (~15 mol m^2 d^{-1}) was more than the minimum light required for growth but still far from the optimal value. So in an effort to receive more light, the shoot height of the CK plants was longer than the shoot height of the T1, T2, and T3 plants. At S1, however, the average indoor DLI (~8 mol m^2 d^{-1}) was so low that it did not even provide the minimum light for plant growth.

Table 7. The normality test for chlorophyll and chlorophyll fluorescence parameters of sweet pepper seedlings exposed to different quality of supplemental light.

Normalization test	Parameters							
	F_0	F_m	F_v	F_v/ F_m	Chl. a (mg ml^{-1})	Chl. b (mg ml^{-1})	Chl. a/ Chl. b	Chl. totall (mg ml^{-1})
Skewness	0.275	-1.28	-1.241	-1.267	-1.099	-0.387	-1.038	-0.475
Kurtosis	-1.006	0.191	0.132	0.446	-1.440	-0.621	-0.469	-0.378

Table 8. Variance analysis for chlorophyll and chlorophyll fluorescence parameters of sweet pepper seedlings exposed to different quality of supplemental light.

Source of variation	Df	Mean Square (MS)							
		F_0	F_m	F_v	F_v/ F_m	Chl. a (mg ml^{-1})	Chl. b (mg ml^{-1})	Chl. a/ Chl. b	Chl. totall (mg ml^{-1})
Season	1	147.0**	4543**	6325**	0.002**	0.312**	0.042**	0.002^{ns}	0.58**
Season Error	4	9.83	74.42	116.9	0.001	0.006	0.001	0.001	0.011
Light	3	643.9**	63952**	76613**	0.013**	1.96**	0.102**	0.112**	2.95**
Light × season	3	14.61^{ns}	2391**	2346**	0.001**	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}
Light × season Error	12	8.77	63.37	95.92	0.001	0.003	0.005	0.005	0.01
Cultivar	1	10.09^{ns}	1.75^{ns}	3.52^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}
Season × Cultivar	1	0.19^{ns}	22.75^{ns}	22.69^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}
Light × Cultivar	3	11.41^{ns}	43.14^{ns}	79.82^{ns}	0.001^{ns}	0.001^{ns}	0.002^{ns}	0.002^{ns}	0.002^{ns}
Season × Light × Cultivar	3	4.58^{ns}	7.96^{ns}	17.08^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}	0.001^{ns}
Residual Error		14.96	49.12	46.69	0.001	0.004	0.004	0.007	0.006
Coefficient of variation	-	2.95	1.11	1.47	0.87	1.27	3.11	3.64	1.14

^{ns}, *, **: Non significant and significant at 5% and 1% probability level, respectively.

Table 9. Interactive effect of season × light on mean values of some chlorophyll fluorescence parameters of sweet pepper seedlings exposed to different quality of supplemental light.

Chlorophyll Fluorescence parameters	season	Light Treatment				F value	Pr
		T1	T2	T3	CK		
Fm	S1	701.17[b]	707.33[b]	738.83[a]	544.67[c]	670.17	0.0001
	S2	709.00[b]	712.50[b]	741.17[a]	606.32[c]	683.57	0.0001
Fv	S1	565.50[b]	576.17[b]	614.17[a]	402.33[c]	526.01	0.0001
	S2	578.67[b]	586.50[b]	618.00[a]	466.83[c]	911.84	0.0001
Fv/Fm	S1	0.806[b]	0.815[b]	0.832[a]	0.738[c]	132.72	0.0001
	S2	0.816[b]	0.823[ab]	0.834[a]	0.770[c]	267.13	0.0001

Data are shown as treatment average of three replicates; mean values followed by different. letters in the same entry indicate significant differences by the Tukey's test at $p \leq 0.01$ or $p \leq 0.05$.

S1: The average indoor DLI < 10 mol m^2 d^{-1} (range of 8-9 mol m^2 d^{-1})

S2: The average indoor DLI > 10 mol m^2 d^{-1} (range of 14-16 mol m^2 d^{-1})

Table 10. Individual effects of supplementary light on mean values of chlorophyll parameters of sweet pepper seedlings exposed to different qualities of supplemental light.

Light treatment	Chlorophyll parameters			
	Chl. a (mg ml^{-1})	Chl. b (mg ml^{-1})	Chl. a/ Chl. b	Chl. totall (mg ml^{-1})
T1	4.99[a]	2.16[a]	2.31[a]	7.15[a]
T2	5.02[a]	2.17[a]	2.31[a]	7.18[a]
T3	5.03[a]	2.17[a]	2.32[a]	7.21[a]
CK	4.21[b]	1.98[b]	2.12[b]	6.19[b]

Data are shown as average values of three replicates. Mean values followed by different letters in the same column indicate significant differences by Tukey's test ($p \leq 0.01$).

Table 11. Individual effects of season on mean values of chlorophyll parameters of sweet pepper seedlings exposed to different qualities of supplemental light.

Season	Chlorophyll parameters			
	Chl. a (mg ml^{-1})	Chl. b (mg ml^{-1})	Chl. a/ Chl. b	Chl. totall (mg ml^{-1})
S1	113.55	50.18	54.27	163.73
S2	117.42	51.6	54.57	169.02

Data are shown as treatment average of three replicates.

S1: The average indoor DLI < 10 mol m^2 d^{-1}

S2: The average indoor DLI > 10 mol m^2 d^{-1}

This observation agrees with earlier findings by Tang et al. (2019) who investigated the physiological and growth response of *Capsicum annuum* L. to supplementary light. In this research, control plants (7 h white LED, 300 μmol m^{-2} s^{-1} equal to 7.5 mol m^2 d^{-1}) had the lowest values of growth parameters compared with T1 plants (7 h white LED + 1 h R4B1), T2 plants (7 h white LED + 3 h R4B1), and T3 plants (7 h white LED + 5 h R4B1).

In addition, studying the differences between the means of stem height at S2 showed a significant difference among T1, T2, and T3 plants, so that T3 (30% blue light) had the shortest stem height. The wavelength of blue LEDs in the present study is within the domain of activity of cryptochromes. Thus, the inhibition of stem height with the increase of blue LEDs is probably attributed to the stimulated blue-sensitive receptors (cryptochrome receptors) that have maximal activity in the presence of blue light and strongly prevent plant elongation (Ahmad et al., 2002; Naznin et al., 2019). Previous research has shown an increase in plant height under 100% red light (Chatterjee et al., 2006; Poudel et al., 2008). Pepper plants grown under 100% red light showed greater plant height than those grown under R90B10 light (Brown et al., 1995). Similarly, cherry tomato plants grown under 100% red light were taller than those grown under an equal mixture of red and blue light (Liu et al., 2009). In this regard, the plant height of lettuce, kale, and pepper increased with increasing red light, and the highest plant height was observed under the treatment of 0% blue LEDs (Hosseini et al., 2018; Naznin et al., 2019; Seif et al., 2021).

Differences between the means of specific leaf area at all levels of supplemental light was significantly lower than control treatment. It has been found that low light levels may lead to an increase in specific leaf area and plant height. These adaptations maximize available light absorption and meet the demand for photosynthesis (Steinger et al., 2003). This is while the reduction in specific leaf area can protect the plant from high radiation (Matos et al., 2009; Wentworth et al., 2006). Fan et al. (2013) investigated the effect of a combination of blue and red lights on tomato plants and found that when the photosynthetic photon flux density increased from 50 to 550 μmol m^{-2} s^{-1}, the specific leaf area decreased (Fan et al., 2013). However, Llewellyn et al. (2019) did not observe any increase in specific leaf area for any of the cultivars studied by researching gerbera plants under LED supplemental light treatment (Llewellyn et al., 2019).

The results of this research showed that chlorophyll fluorescence parameters were sensitive to light and these parameters at all levels of supplementary artificial light were significantly higher than the control treatment in both cultivars, but no significant difference was observed between the two pepper cultivars.

The Fm and Fv parameters were significantly higher in T3 plants than in T1 and T2 plants, and the maximum quantum yield of photosystem II (Fv/Fm) achieved a similar result. The “red light syndrome” occurs in plants grown under 100% monochromatic red light, and strong decreases in photosynthetic capacity are one of the symptoms of this physiological deficiency (Aliniaeifard et al., 2018; Ouzounis et al., 2015; Trouwborst et al., 2016). The addition of blue to red light leads to leaf expansion, stomatal opening, easier access to CO_2, and increased photosynthesis (Boccalandro et al., 2012; Savvides et al., 2012). Previous research confirmed the positive effect of blue light on photosynthetic capacity and Fv/Fm (Aalifar et al., 2020 a, b; Kaiser et al., 2019; Trouwborst et al., 2016).

Low light intensity caused lower chlorophyll levels and photosynthetic functionality in S1 compared to S2, especially in the control treatment. Light plays an important role in the regulation of chlorophyll synthesis, such that the transcription of key enzyme genes involved in chlorophyll biosynthesis occurs at higher levels in light than in the dark (Apitz et al., 2014; Stephenson and Terry, 2008). Chlorophyll is responsible for absorbing light and transferring electrons in reaction centers (Evans, 1988; Fromme et al., 2003), regulating the expression of genes related to photosynthesis through plastid signals (Zhang et al., 2006), stabilizing proteins in chloroplasts, and maintaining the structure and function of chloroplasts (Reinbothe et al., 2006). Thus, plants grown under sufficient light generally have more chlorophyll a, total chlorophyll, and photosynthesis, resulting in higher plant biomass (Tang et al., 2019).

Supplementary lighting is important in promoting growth and development of horticultural plants (Garcia and Lopez, 2020; Hammock et al., 2021; Hernandez et al., 2020; Javadi Asayesh et al., 2021; Kim et al., 2020; Sobczak et al., 2021). Similarly, the results of our experiments on sweet pepper seedlings showed that the portion of blue light is also important.

Conclusion

This research showed that the application of supplementary red: blue lighting (7: 3) is optimal for pepper seedling growth under greenhouse conditions in the north of Iran, especially during the winter.

Conflict of interest

The authors indicate no conflict of interest for this work.

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