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Enhancement of Snapdragon Photosynthesis Efficiency, Growth, and Biochemical Properties by LED Lights and Carbon Nanotubes

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ABSTRACT

Antirrhinum majus (*snapdragon*) is a perennial plant from the Scrophulariaceae family. It is commonly cultivated annually in colder regions while valued for its ornamental and biochemical traits. This study investigated the effects of various LED light spectra (white, blue, red, 80% blue + 20% red, 60% blue + 40% red, 40% blue + 60% red, 20% blue + 80% red) and single-walled carbon nanotube concentrations (0, 50, 100 mg L^{-1}) on photosynthesis efficiency, morphological growth, and biochemical properties of this plant. The experiment was conducted using a completely randomized factorial design with four replications in the greenhouse of Mohaghegh Ardabili University, Iran, from May to September 2024. Seeds were sown in trays and transplanted at the 4-leaf stage into pots containing a 1:1:1 mixture of organic matter, sand, and soil. Data were analyzed using SAS software with Duncan's test. Results revealed significant interaction effects of light and carbon nanotubes on morphological features, i.e., flower count, plant height, fresh weight, and flower diameter, as well as biochemical traits, i.e., sugar content, flavonoids, phenols, antioxidants, and anthocyanins. Chlorophyll fluorescence parameters (F_m, F_v, and F_v/F_m) were also affected. The highest flower count (23) was observed under 100% red light without nanotubes, while the maximum fresh weight (41.46 g) was recorded under 20% red + 80% blue light. Blue light combined with 50 mg L^{-1} nanotubes maximized stem and flower diameter, whereas biochemical properties and F_v/F_m were optimized under blue-red combinations while using a nanotube concentration of 100 mg L^{-1}. The highest F_m and F_v occurred under 40% red + 60% blue light. The findings suggested that red light alone enhanced morphological growth without nanotubes, while blue-red combinations with the 100 mg L^{-1} nanotube concentration were more effective for improving biochemical traits and photosynthesis efficiency, including chlorophyll fluorescence dynamics. The heat map analysis revealed that morphological traits, such as plant height, flower count, and fresh weight correlated significantly ($r > 0.7$, $P < 0.01$) with biochemical parameters, i.e., total phenol content, flavonoid concentration, and DPPH antioxidant activity. The findings suggested that these traits showed a coordinated response to nanoparticle treatments. Thus, these results are favorable for optimizing snapdragon cultivation in controlled environments.

Abbreviations Carbon nanotubes (CNT), Fresh weight (FW), Light-emitting diodes (LED), Total antioxidant capacity (TAC), Total flavonoids content (TFC), Total phenol content (TPC)

Introduction

Snapdragon (*Antirrhinum majus*), a member of the Scrophulariaceae family, is a perennial plant that is commonly cultivated as an annual. Plant morphological characteristics can be improved by modifying light quality (Zhang and Van, 2017). Light is also one of the most important factors affecting plant growth and flowering, as plants require light throughout their entire life cycle, from germination to flowering and seed production (Pourbeyrami Hir and Sardari, 2025). However, plant responses vary depending on light intensity and spectral composition. In recent years, the use of artificial lighting in agriculture has increased substantially, particularly for promoting plant growth under conditions of limited natural light (Morrow, 2008).

Wang et al. (2024) investigated the effects of red and blue LED lights on the growth and photosynthetic characteristics of bitter gourd. The experiment included three light spectra: 100% blue, 100% red, and 100% white light, all applied at an intensity of 50 μmol m^{-2} s^{-1}. Compared with white light, stem diameter increased significantly under blue light, whereas germination rate, seedling height, and soluble sugar content increased under red light. Measurements of photosynthetic traits showed that both red and blue light treatments enhanced leaf stomatal conductance. The authors suggested that bitter gourd, being a sun-loving plant with a relatively low dark respiration rate, responds favorably to specific light qualities. Overall, the study concluded that blue light positively affected germination, seedling growth, sexual reproduction, and photosynthetic performance, thereby clarifying the relationship between light quality and sexual reproduction.

The effects of different light spectra on growth indices and antioxidant capacity in *Matricaria chamomilla* were also investigated using white, red + blue, and far-red light treatments. Compared with the other spectra, red + blue light increased fresh weight, dry weight, relative water content, and root length. The highest hydrogen peroxide level was observed under this spectrum, although no significant differences in hydrogen peroxide content were detected among the treatments. The greatest stem length was recorded in seedlings exposed to far-red light. Although white light resulted in the highest antioxidant activity as well as the greatest phenol and flavonoid contents, reduced growth was observed in seedlings treated with white light. This reduction was attributed to the allocation of carbon and energy toward the biosynthesis of antioxidant compounds. Based on these findings, the combined red + blue light spectrum was identified as the most suitable treatment for cultivating *Matricaria chamomilla*.

Sarfaraz et al. (2023) examined the effects of LED lighting on the morphological and physiological characteristics of *Origanum vulgare* L. The treatments included 100% red light, 100% blue light, 70% red + 30% blue light, and fluorescent light as the control. The results showed that seedlings treated with 100% red light exhibited increases in leaf count, fresh weight, root dry weight, and root length. In addition, red light increased dry matter accumulation by 16.53% compared with the control. The highest leaf area, shoot weight, and leaf weight per plant were recorded under 100% blue light. The ratio of root fresh weight to dry weight also increased under blue light, red light, and fluorescent light treatments. Seedlings exposed to the combined red + blue light spectrum showed greater plant height and a 26.58% increase in stem diameter compared with the control. Therefore, the present study aims to investigate the effects of seven different light spectra, including white light, red light, blue light, 80% blue + 20% red light, 60% blue + 40% red light, 80% red + 20% blue light, and 60% red + 40% blue light, in combination with single-walled carbon nanotube treatments, on the growth characteristics of snapdragon.

Materials and Methods

This study was conducted at Mohaghegh Ardabili University, Iran, using snapdragon seeds in a completely randomized factorial design with four replications. The treatments consisted of different LED light spectra, including white, red, blue, 80% blue + 20% red, 60% blue + 40% red, 80% red + 20% blue, and 60% red + 40% blue, along with different concentrations of carbon nanotubes (0, 50, and 100 mg L^{-1}). Seeds were initially germinated in trays and then transplanted at the four-leaf stage into pots containing a 1:1:1 mixture of organic matter, sand, and soil. Plants were grown from May to September 2024 under controlled conditions of 22–25 °C temperature, 60–70% relative humidity, and a 16/8 h light/dark photoperiod. The measured traits included the number of branches, buds, flowers, and secondary branches; final plant height; fresh weight; stem diameter; bud diameter; flower diameter; and several biochemical parameters, including phenol, flavonoid, antioxidant, anthocyanin, photosynthetic efficiency, and soluble sugar contents. The number of flowers and secondary branches was determined by direct counting. Final plant height was measured using a ruler, flower diameter was measured with a caliper, and fresh weight was recorded using a digital balance with a precision of 0.001 g.

Preparation of dry matter

Leaves were dried at 40 °C for 96 h and then ground into powder. A 1 g sample of the dried material was soaked in 50 mL of 80% methanol for 48 h at room temperature. The extracts were filtered using Whatman No. 4 filter paper, and the solvent was evaporated at temperatures below 55 °C. The resulting extracts were stored at 4 °C for subsequent analyses.

Total phenol content (TPC)
Total phenol content was determined according to the method of Meda et al. (2005). Gallic acid was used as the standard, and the results were expressed as mg gallic acid equivalents per g dry weight.

Total flavonoid content (TFC)
Total flavonoid content was measured following the method of Mita et al. (1997). Briefly, 500 µL of extract was mixed with 1.5 mL of 80% methanol, 100 µL of 10% $AlCl_2$, 100 µL of 1 M sodium acetate, and 2.8 mL of distilled water. After incubation for 40 min, absorbance was measured at 415 nm. Quercetin was used as the standard, and the results were expressed as mg quercetin equivalents per g dry matter.

Total antioxidant capacity (TAC)
Total antioxidant capacity was evaluated using the DPPH method described by Miliauskas et al. (2004). Different extract-to-DPPH ratios (3:1, 1.5:1, and 0.75:1) were prepared and mixed with 2 mL of 0.004% methanolic DPPH solution. The mixtures were kept in the dark for 30 min, after which absorbance was measured at 517 nm to determine free radical scavenging activity.

Total anthocyanin content
Anthocyanin content was determined according to the method of Hara et al. (2003). Frozen tissue samples (0.2 g) were homogenized in a 99:1 methanol:HCl solution and centrifuged at 12,000 × g for 15 min. Absorbance of the supernatant was measured at 550 nm using an extinction coefficient of 33,000 cm^{-1} M^{-1}. Anthocyanin content was expressed as µM g^{-1} fresh weight.

Chlorophyll fluorescence
Chlorophyll fluorescence was measured on fully developed leaves using a Hansatech fluorometer. Prior to measurement, leaves were dark-acclimated for 91 s using leaf clips.

Total sugar content
Soluble sugars were extracted from 0.1 g of dried tissue using 10 mL of 70% ethanol over a one-week period with daily stirring. After extraction, the solution was diluted to 2 mL. Subsequently, 1 mL of 5% phenol and 5 mL of 48% sulfuric acid were added. The samples were incubated at 20 °C for 20 min, cooled, and absorbance was measured at 485 nm. Glucose was used as the standard, and total soluble sugar content was expressed as mg g^{-1} dry weight (Irigoyen et al., 1992).

Statistical analysis
Data were processed with two-way ANOVA in SAS 9.01, with means of four replicates (n = 4) compared by Duncan's test ($P \leq 0.05$ (*), $P \leq 0.01$ (**), $P \leq 0.001$ (***), ^{ns}).

Results
The experiment was conducted over two consecutive years. Since the results obtained in the first and second years were similar, only the data from the second year are presented, as additional indices were measured during this period.

Number of flowers
Analysis of variance (ANOVA) revealed a significant interaction between light spectrum and carbon nanotube concentration on the number of flowers (P < 0.01; Table 1). The highest number of flowers (23), representing a 25% increase compared with the control, was observed under 100% red light without carbon nanotube application. Similar values were also recorded under 60% blue + 40% red light and under 100% blue light with 100 mg L^{-1} carbon nanotubes. In contrast, the lowest number of flowers (11.33) was observed under 20% blue + 80% red light in combination with 100 mg L^{-1} carbon nanotubes (Table 2).

Plant height
Light and interaction effects were significant (Table 1). The tallest plants (26.56 cm) were observed under 100% blue light with 50 mg L^{-1} nanotubes, and the shortest (13.73 cm) under 20% red + 80% blue light without nanotubes (Table 2).

Fresh weight of aerial part
Light and interaction effects were significant (Table 1). The highest weight (41.46 g) occurred under 20% red + 80% blue without nanotubes, and the lowest (25.2 g) under 60% red + 40% blue without nanotubes (Table 2).

Flower diameter
Significant effects ($P < 0.01$) were observed (Table 1). The maximum diameter (35.37 mm) was observed under 100% blue with 50 mg L^{-1} nanotubes (Fig. 1A).

Table 1. Analysis of variance for the effect of light and carbon nanotubes on morphological indices in snapdragon.

Sources of variation	**DF**	**Number of flowers**	**Number of branches**	**Plant height**	**Fresh weight aerial part**	**Flower diameter**
Light	6	32.64**	8.75*	57.14**	92.67**	86.96**
Carbon nanotubes	2	8.04^{ns}	35.49**	5.94^{ns}	0.003^{ns}	104.92**
Light x carbon nanotube	12	29.06**	9.28**	16.82**	48.65**	27.51**
Error	42	3.96	3.90	4.59	9.94	9.62
Coefficient of variation	_	12.63	15.18	10.69	9.64	10.06

[1] ^{ns}, *, and ** respectively, no significant difference and significant difference at the probability level of 0.05 and 0.01.

Table 2. Comparison of means for the effect of light and carbon nanotubes on morphological traits in snapdragon.

Carbon nanotubes	**LED**	**Number of flowers**	**Number of branches**	**Plant height (cm)**	**Fresh weig ht (gr)**	**F_v/F_m (ms)**
CNT0	W100	12.66^{ef}	8.66^{b-e}	19.50^{c-g}	32.64^{b-e}	0.70^{f}
	B100	13.66d^{ef}	10.66^{de}	23.20^{ab}	33.26^{c-e}	0.82^{ab}
	R100	23^{a}	16.33^{a}	22.70^{a-c}	34.43^{c-e}	0.81^{c}
	R80B20	15.33^{c-e}	10.66^{b-d}	21.66^{b-d}	31.64^{cd}	0.77^{cd}
	R60B40	13.66^{d-f}	10.66^{de}	16.60^{e-h}	25.20^{f}	0.83^{ab}
	R40B60	19.66^{ab}	13.33^{a-d}	18.96^{c-g}	30.16^{d-f}	0.82^{ab}
	R20B80	17.33^{b-d}	11^{c-d}	13.73^{h}	41.46^{a}	0.81^{a-c}
CNT50	W100	14.3^{d-f}	14.33^{a-d}	20.40^{b-f}	32.74^{c-e}	0.75^{de}
	B100	18.33^{bc}	12.66^{a-d}	26.56^{a}	40.55^{ab}	0.81^{a-c}
	R100	15.33^{c-e}	14.33^{a-h}	17.40^{e-h}	25.53^{f}	0.82^{ab}
	R80B20	13.33^{ef}	15^{ab}	20.14^{b-f}	30.14^{a-c}	0.82^{a-c}
	R60B40	12.33^{ef}	14.33^{a-d}	19.40^{h}	29.25^{ef}	0.82^{ab}
	R40B60	16^{b-e}	14^{ab}	20.70^{b-f}	30.43^{c-f}	0.81^{a-c}
	R20B80	18.33^{bc}	14.66^{a-c}	16.53^{f-h}	40.30^{ab}	0.81^{a-c}
CNT 100	W100	16^{b-e}	12^{b-e}	22.96^{a-c}	35.05^{b-d}	0.82^{ab}
	B100	22^{a}	3.33^{a-d}	20.30^{b-f}	29.66^{d-f}	0.82^{ab}
	R100	14.33^{d-f}	12.66^{a-d}	20.73^{b-e}	30.73^{c-f}	0.72^{ef}
	R80B20	11.33^{f}	16.43^{ab}	23.33^{ab}	33.30^{c-e}	0.80^{a-c}
	R60B40	15.33^{c-e}	12.33^{b-e}	22.63^{a-c}	30.23^{f}	0.81^{a-c}
	R40B60	14.66^{c-f}	12^{b-e}	18.14^{d-g}	36.46^{c-e}	0.83^{a}
	R20B80	14^{d}	14^{a-d}	15.60^{f-h}	32.90^{c-e}	0.78^{b-d}

*Common letters are not significantly different from each other.

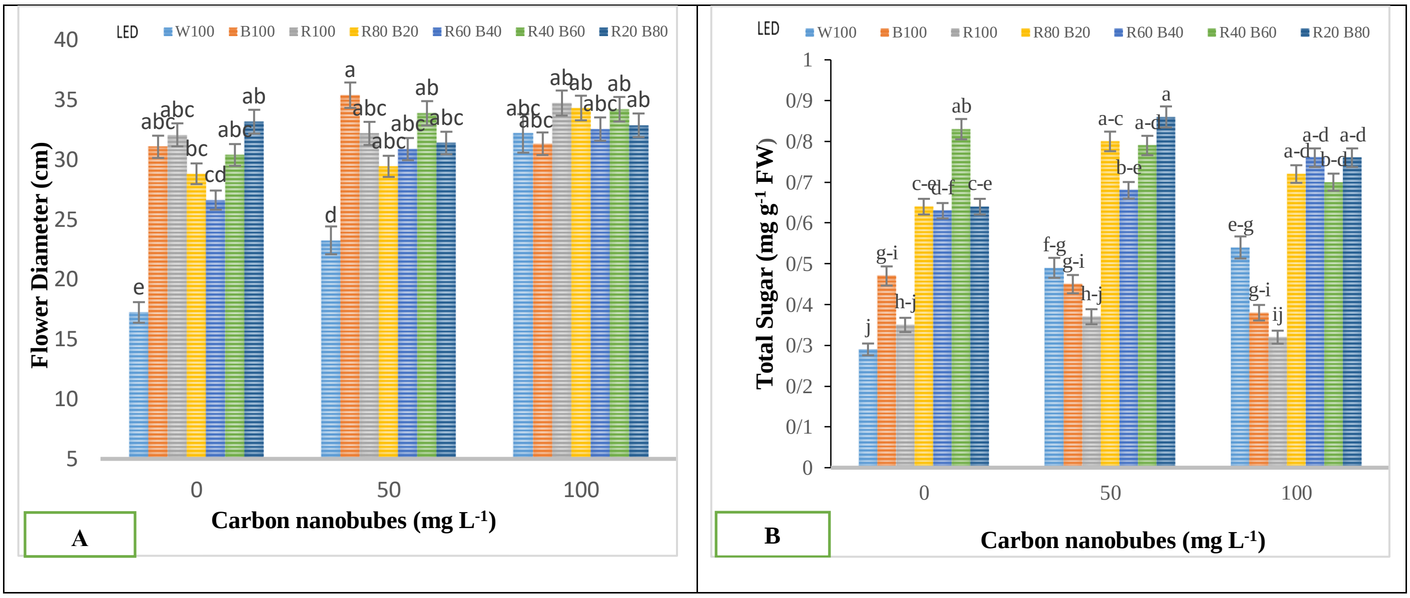

Fig. 1. The interaction effects of light and carbon nanotubes on flower diameter (A) and total sugar content (B) in snapdragon.

Total sugar content

All effects were significant (Table 3). The highest content (0.86 mg g^{-1} FW) occurred under 20% red + 80% blue with 50 mg L^{-1}, and the lowest (0.29 mg g^{-1} FW) was observed under 100% blue without nanotubes (Fig. 1B).

Flavonoids content

Significant effects (Table 3) showed the highest content (6.37 mg g^{-1} FW) under 60% blue + 40% red without nanotubes, and the lowest (2.77 mg g^{-1} FW) under 100% white with 50 mg L^{-1} (Fig. 2A).

Table 3. Analysis of variance for the effect of light and carbon nanotubes on biochemical indices in snapdragon flowers.

Sources of changes	DF	Total sugar	Total Flavonoid Content	Total Phenol Content	Antioxidant capacity	Anthocyanin	F_m	F_v	F_v/F_m
Light	6	0.292**	10.68**	102.47**	647.85**	45.14**	43409/68**	60890874**	0/004**
Carbon nanotubes	2	0.036**	1.53**	21.06**	130.52**	22.24**	60907/47**	475/00ns	0/0006ns
Light x carbon nanotube	12	0.017**	0.59**	28.63**	82.15**	9.93**	14629/39ns	38825/28**	0/003**
Error	42	0.007	0.26	4.49	19.95	3.47	10817/53	3326/85	0/0005
Coefficient of variation	_	13.89	11.53	17.35	11.08	12.81	5/25	5/09	2/95

ns, *, and ** respectively, no significant difference and significant difference at the probability level of 0.05 and 0.01.

Phenolic compound content

Significant effects ($P < 0.01$, Table 3) showed the highest content (19.42 mg g^{-1} FW) under 80% blue + 20% red with 50 mg L^{-1}, and the lowest (4.78 mg g^{-1} FW) under 100% white without nanotubes (Fig. 2B).

Antioxidant capacity

Analysis of variance indicated that DPPH activity was significantly influenced by the individual effects of light spectrum and carbon nanotube concentration, as well as by their interaction effect (Table 3). The lowest DPPH activity was recorded under 100% white light without carbon nanotube application, which was significantly lower than that of the other treatments (Fig. 3A). In contrast, the highest DPPH activity was observed under 40% red + 60% blue light in the absence of carbon nanotubes (Fig. 4).

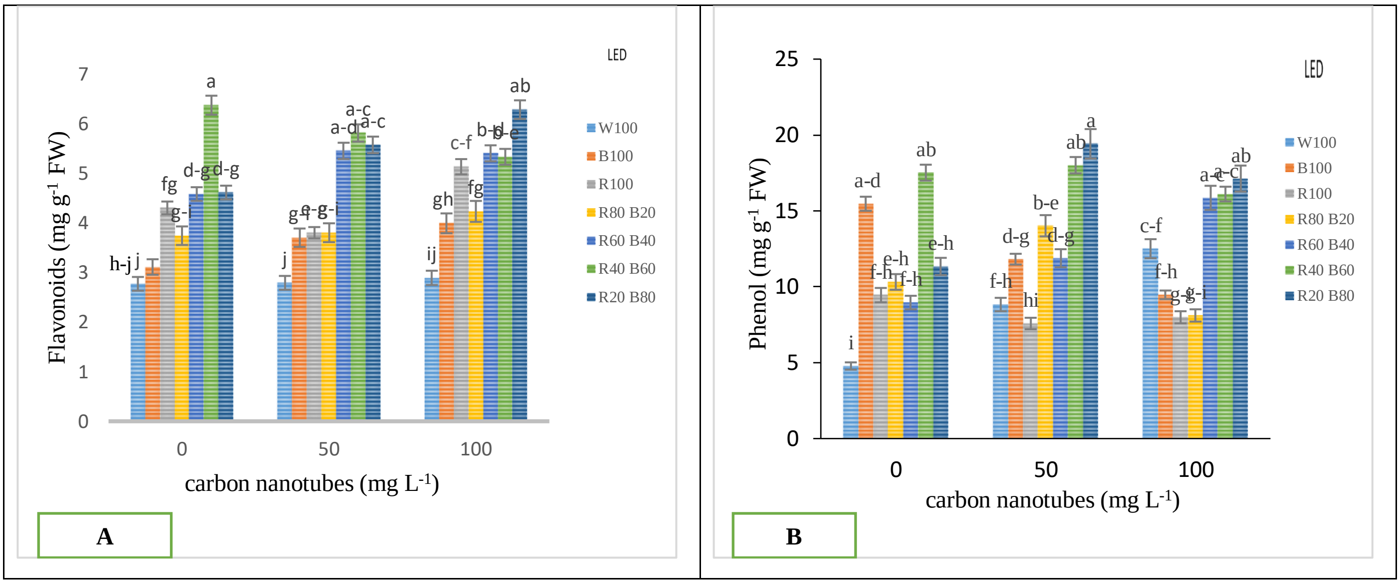

Fig. 2. The interaction effects of light treatments and carbon nanotubes on flavonoid (**A**) and phenol content (**B**) of snapdragon.

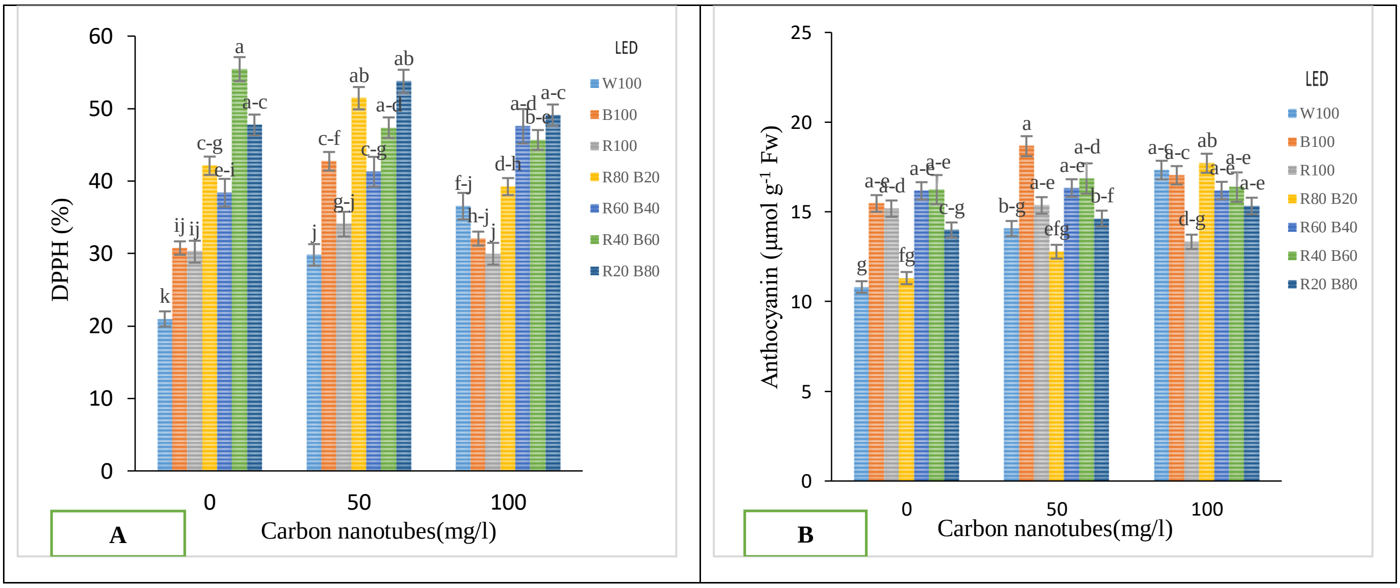

Fig. 3. The interaction effects of light treatments and carbon nanotubes on DPPH (**A**) and anthocyanin (**B**) content of snapdragon.

Anthocyanin content

Analysis of variance showed that anthocyanin content was significantly affected by the individual effects of light spectrum and carbon nanotube concentration, as well as by their interaction effect (Table 3). The lowest anthocyanin content was recorded under 100% white light without carbon nanotube application, which was significantly lower than that of the other treatments (Fig. 3B). In contrast, the highest anthocyanin content was observed under 100% blue light in combination with 50 mg L^{-1} carbon nanotubes (Fig. 4).

F_V

According to the results of the analysis of variance (Table 3), stomatal conductance was significantly affected by the effect of light and by the interaction between light and carbon nanotubes, whereas the main effect of carbon nanotubes alone was not significant. The highest F_v index was observed under 100% red light with the application of 0.1 mg L^{-1} carbon nanotubes. In contrast, the lowest F_v index was recorded under 100% white light without the application of carbon nanotubes (Fig. 5A).

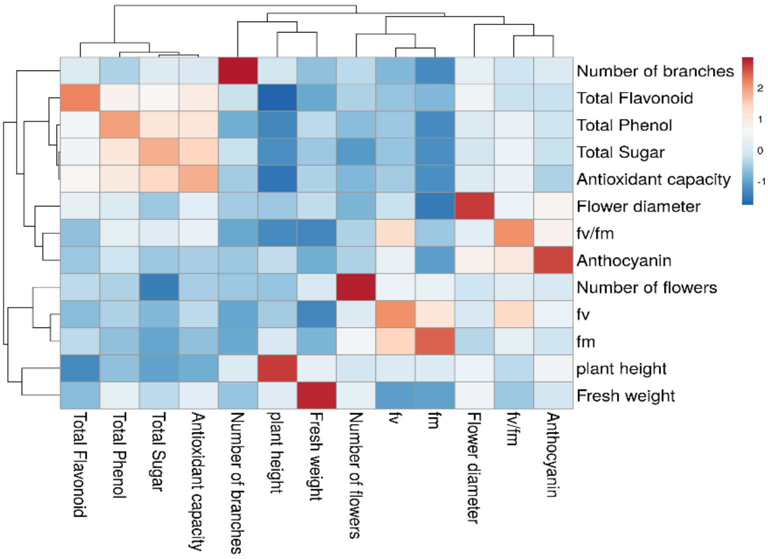

Fig. 4. Correlation of morphological and biochemical variables in snapdragon (*Antirrhinum majus*) under various conditions.

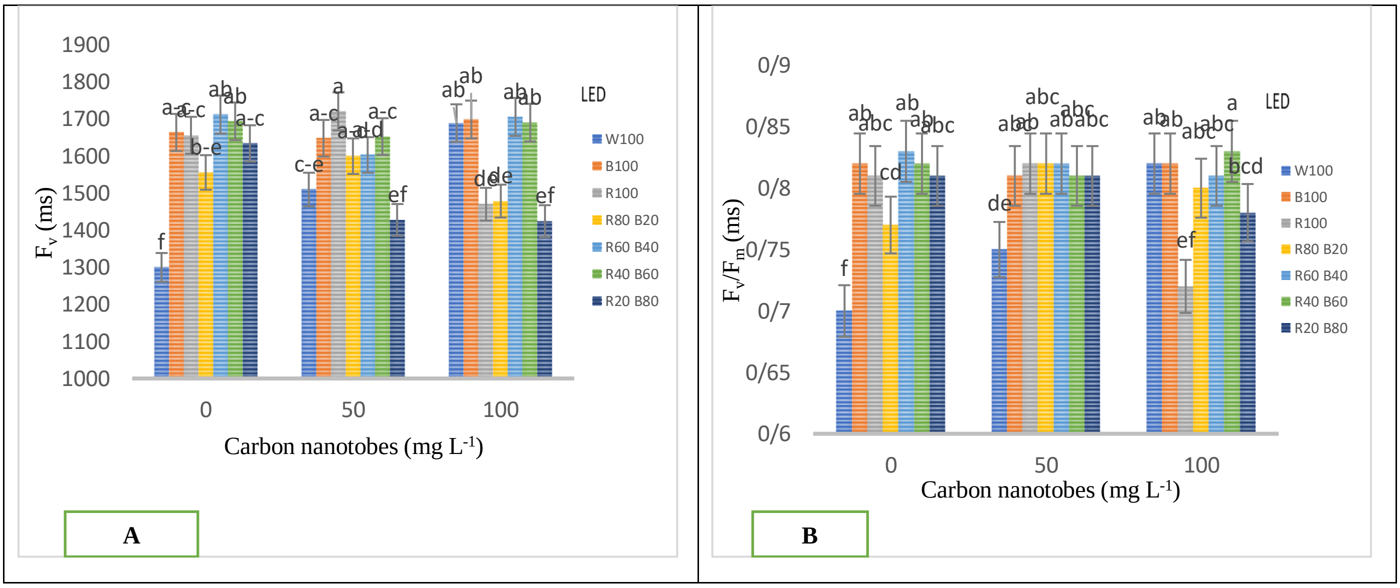

Fig. 5. The interaction effects of light treatments and carbon nanotubes on (**A**) F_v and (**B**) F_v/F_m of snapdragon.

F_m

The analysis of variance indicated that the F_m trait was significantly affected by the light treatments and by the interaction between light and carbon nanotubes, whereas the main effect of carbon nanotubes alone was not significant (Table 3). As shown in Figure 5B, the highest F_m value was observed under 40% red + 60% blue light, although it did not differ significantly from the treatments with 100% red light, 100% blue light, and 20% red + 80% blue light. The lowest F_m value was recorded under 20% red + 80% blue light. Application of carbon nanotubes generally reduced the F_m index. The highest F_m value was observed in the control treatment without carbon nanotube application, which did not differ significantly from the treatment with 100 mg L^{-1} carbon nanotubes. In contrast, the lowest F_m value was recorded in the treatment with 50 mg L^{-1} carbon nanotubes (Fig. 5B).

F_v/F_m

The highest F_v/F_m ratio was observed under 40% red + 60% blue light in combination with 100 mg L^{-1} carbon nanotubes. In contrast, the lowest F_v/F_m ratio was recorded under 100% white light without carbon nanotube application (Fig. 6A). Heat map analysis of the correlation coefficients among the evaluated traits revealed a strong positive relationship among growth-related parameters, including plant height, fresh weight, and number of flowers, indicating coordinated vegetative and reproductive development. Total phenol content, total flavonoid content, and antioxidant capacity were also highly correlated and formed a distinct cluster, suggesting that enhanced antioxidant potential was primarily associated with phenolic metabolism. In addition, anthocyanin content showed a moderate positive correlation with photosynthetic efficiency indices (F_v, F_m, and F_v/F_m), indicating its possible protective role against photo-oxidative stress. In contrast, weak negative correlations were observed between certain biochemical traits, particularly phenolic compounds, and morphological characteristics, which may reflect a trade-off between secondary metabolite production and structural growth under different light conditions (Fig. 4).

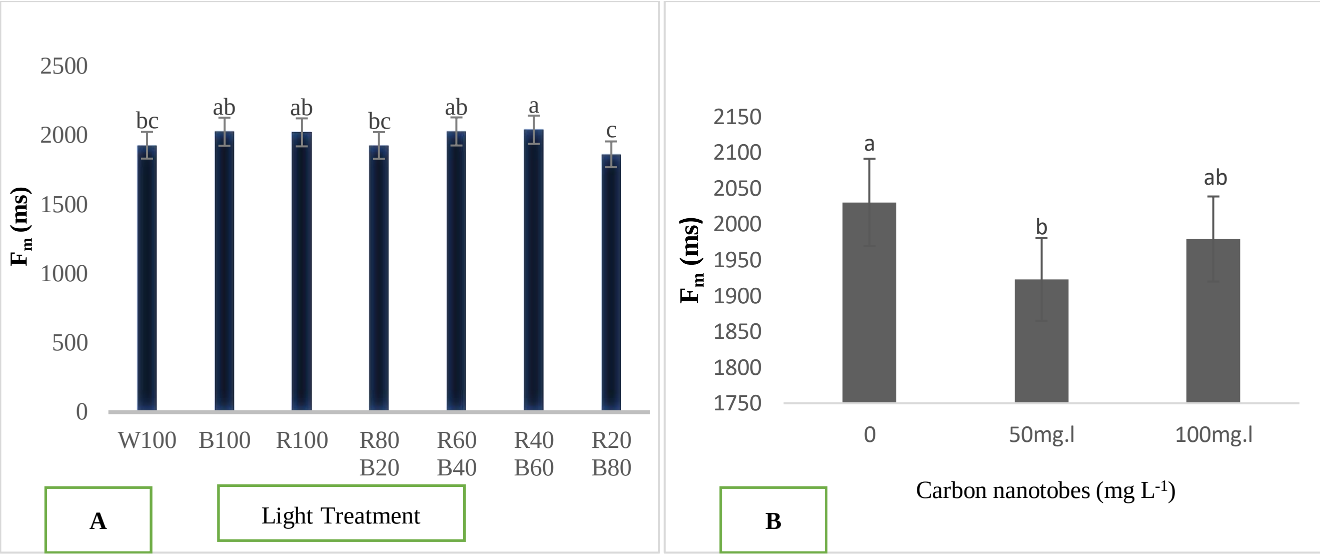

Fig. 6. The effects of light treatments (**A**) and carbon nanotubes (**B**) on F_m of snapdragon plant.

Discussion

Light quality influences numerous morphological and biochemical traits during plant growth and development. In recent years, the use of supplementary lighting has substantially improved crop yield and quality under conditions of limited natural light, particularly during autumn and winter. Among artificial lighting systems, light-emitting diodes (LEDs) have emerged as promising alternatives for use in controlled agricultural environments. The development of LED technology has created new opportunities for the cultivation of medicinal, horticultural, and ornamental plants under controlled conditions, while also enabling detailed studies on the physiological effects of different light wavelengths on plants. Exposure to either blue or red light alone can promote plant growth, owing to the ability of these spectra to satisfy specific light requirements of plants. However, several researchers have suggested that a combination of blue and red light is essential for optimal plant growth and development (Massa et al., 2008). In the present study, both red and blue light significantly influenced plant growth and development. For instance, exposure to red light alone significantly increased plant height compared with other light treatments. Johkan et al. (2010) also reported that increasing red light exposure enhanced plant height and fresh weight. Increased plant height is generally associated with improved photosynthesis, growth, and overall plant development (Adams et al., 2008). Similarly, several studies have demonstrated that red light enhances plant growth by increasing fresh weight, dry weight, and plant height (Heo et al., 2002; Son and Oh, 2013).

In the current study, blue light alone also increased plant height compared with several other treatments. This response may be associated with hormonal regulation, particularly changes in gibberellin biosynthesis and signaling. Plant responses to blue light can vary depending on species and developmental stage, and these responses are closely linked to the expression and activity of gibberellin-related genes. Previous studies have shown that increasing the proportion of red light relative to far-red light, either through day extension or night interruption treatments, promotes vegetative growth and flowering. Blue light (400–500 nm) has been reported to suppress excessive vegetative growth, although its influence on flowering remains less clearly defined. Runkle and Heins (2001) investigated the effects of red, far-red, and blue light on stem production and flowering in petunia, starflower, bean, pea, and pansy. Their results showed that red light promoted plant growth, whereas far-red light reduced growth per stem but increased stem number. In combination with blue light, changes in the red to far-red ratio increased stem number without significantly affecting flowering percentage or flowering time. In addition, a high red to far-red ratio delayed flowering

initiation. These findings indicate that, in long-day plants, red to far-red ratios and blue light independently regulate plant growth and stem development, while far-red light may inhibit flowering initiation and development in certain species. Cañas et al. (2008) reported that blue light accelerated bud emergence and improved flower coverage, flower number, and leaf greenness. Furthermore, combined red and blue light treatments showed favorable effects on flowering and growth traits, which is consistent with the findings of the present study. The effects of nanoparticles on plant growth and development vary depending on plant species and nanoparticle type. Nanoparticles have been reported to influence traits such as germination, seedling growth, and rooting. For example, under red light conditions, the essential oil content of peppermint clones increased more than fourfold compared with field conditions. In the same study, the highest fresh weight was obtained under combined red and blue light treatments. Blue light also significantly increased the activities of catalase, glutathione reductase, and ascorbate peroxidase enzymes in peppermint plants compared with other growth environments, although its effect on superoxide dismutase activity was lower than that observed under fluorescent light (Wang et al., 2024).
Previous studies have demonstrated that combined blue and red light is beneficial for cucumber seedling growth, significantly increasing plant height and biomass quality compared with treatments using red or blue light alone (Tabbert et al., 2022). In addition, Song et al. (2017) reported that white LED light was more suitable for producing high-quality seedlings than treatments lacking green light or those with a high blue-to-red light ratio. LED light spectra have also been recognized as effective light sources for plant research in the International Space Station and controlled life-support systems. Soltani et al. (2021) investigated the effects of different light spectra on growth parameters and antioxidant activity in *Anthemis gilanicum*. Their results showed that the combined red + blue light spectrum increased fresh weight, dry weight, relative water content, and root length compared with other light treatments. The highest DPPH radical scavenging activity was observed under white light, while seedlings treated with far-red light exhibited the greatest stem length. The reduced growth observed under white light was attributed to the diversion of carbon and energy resources toward the biosynthesis of antioxidant compounds.

Blue and red light are known to influence proton flux in epidermal cells through decoupling mechanisms, thereby affecting leaf development. Blue light directly interacts with proton pumps and also indirectly regulates them through the modulation of potassium and calcium ion channels, influencing passive ion transport. The important role of blue light in improving photosynthesis and plant development has been well documented (Miao et al., 2016). In the present study, blue light alone effectively increased plant height and fresh weight. Furthermore, recent studies have shown that blue and orange light enhance carbohydrate translocation from leaves more effectively than white light (Lanoue et al., 2018). Zhang and Van (2017) evaluated the effects of light quality on flower morphology, photosynthetic efficiency, and leaf antioxidant capacity under four light spectra, including 100% blue, 100% red, 75% red + 25% blue, and 100% white light, at an intensity of 100 µmol m^{-2} s^{-1} under a 14 h photoperiod. Their findings indicated that red light reduced leaf area, while the thinnest leaves were produced under white light. Blue light increased proline accumulation, whereas carotenoid content, total flavonoids, and phenolic compounds were highest under white light conditions.

Similarly, Heo et al. (2002) reported that the dry weight of marigold seedlings grown under FLR, FLB, and FLFr treatments was higher than that observed under other light treatments. However, seedlings grown under red light (R), fluorescent red light (FLR), and fluorescent light (FL) showed lower dry weight compared with those grown under blue light. In addition, the stem length of seedlings grown under monochromatic blue light was approximately three times greater than that of seedlings grown under FLR or FL treatments. In sage, increased stem elongation was observed under fluorescent far-red light (FLFr), whereas stem length was significantly reduced under red light treatments.

Dehkhodaei et al. (2019) compared the effects of LED light spectra with natural greenhouse light on the quality of petunia and pansy seedlings. The treatments included natural greenhouse light (control), a 50% blue + 50% red LED combination, and 100% white LED light. In petunia seedlings, leaf area, plant height, internode length, stem diameter, and fresh shoot weight were significantly higher under 100% white light compared with the combined blue and red LED treatment and natural greenhouse light. However, the highest number of leaves (21), substrate dry weight (0.17 g), fresh weight (1.65 g), and root dry weight (0.11 g) were obtained under the 50% blue + 50% red light combination. In pansy seedlings, white light also enhanced leaf area, fresh shoot weight, and root dry weight. Ghasemi et al. (2020) investigated the effects of light intensity and ascorbic acid on growth and flowering characteristics of zinnia plants. Their findings showed that reducing light intensity increased root length and volume, fresh and dry weight of leaves, stems and roots, stem diameter, leaf count, plant height, specific leaf area, and flower diameter. The highest fresh and dry weight and flower diameter were recorded at a light intensity of 1200 µmol m^{-2} s^{-1} compared with 600 and 1800 µmol m^{-2} s^{-1}. Lower light intensity delayed bud appearance and full flower opening but increased flower longevity. Overall, although zinnia plants exhibited optimal vegetative growth under full light conditions (1800 µmol m^{-2} s^{-1}), flowering quality and growth performance were superior at 1200 µmol m^{-2} s^{-1}, indicating that successful cultivation is possible under partial shade conditions.

Mahdavifard (2020) reported that red light and combined red + blue light represented the most effective light treatments for the production of three mint species under multilayer cultivation systems using LED lighting. In another study examining the effects of different light spectra on the rose cultivar 'Samurai', chlorophyll a fluorescence techniques were used to evaluate photosynthetic efficiency. The results demonstrated that red light produced the highest energy absorption index and electron transport rate relative to the reaction center. Furthermore, the highest anthocyanin and soluble carbohydrate contents, along with the lowest membrane peroxidation, hydrogen peroxide accumulation, and photosynthetic pigment degradation, were observed under red light conditions. These findings suggested that red light effectively reduced photon damage in rose plants.

The effects of carbon nanotubes on seed dormancy and plant growth have also been investigated in several species. Ghasemi et al. (2020) compared carbon nanotube treatments with sulfuric acid and potassium nitrate for breaking seed dormancy in *Myrtus communis* L. Their results showed that treatment with 0.2% potassium nitrate for 24 h and 0.1 g L^{-1} carbon nanotubes significantly increased germination percentage, germination rate, root length, shoot length, and seedling dry weight. Microscopic examination of the seed endocarp indicated that carbon nanotubes were capable of adhering to and penetrating seed tissues, thereby facilitating the overcoming of physical seed dormancy (Ghasemi et al., 2020).

Conclusion

In conclusion, the use of supplementary lighting significantly improved the morphological and biochemical characteristics of snapdragon plants, enhancing overall plant quality under conditions of low natural light. These findings highlight the potential application of supplementary lighting systems in snapdragon production, particularly during autumn and winter when natural light availability is limited. Light-emitting diodes can therefore be considered effective alternative light sources for controlled agricultural environments. The results demonstrated that both red and blue light significantly influenced the growth and development of snapdragon plants. Red light promoted vegetative growth and flowering characteristics, while blue light alone increased plant height compared with several other light treatments. In addition, the combination of red and blue light produced the highest fresh weight, indicating that balanced spectral combinations are more effective for optimizing plant growth and biomass accumulation than monochromatic light treatments alone.

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Author Contributions

Data curation and writing, SS; conceptualization, methodology, data analysis, data curation, project administration, resources, funding acquisition, writing, and editing, YP; methodology, investigation, review, and editing, EC; writing, review, and editing, SL. All authors have read and agreed to the published version of the manuscript.

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Conflict of Interest

The authors indicate no conflict of interest in this work.

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Supplementary Materials

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