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Research Article

Improving quality parameters of spinach by adjusting light spectra under moderate water deprivation conditions

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Abstract

Spinach (*Spinacia oleracea* L.) is a highly valuable leafy vegetable, abundant in vitamins, minerals, and antioxidants, offering various health benefits such as enhancing cardiovascular health, reducing inflammation, and aiding digestion. Consequently, it is crucial to effectively cultivate and maintain spinach's quality. Light plays a pivotal role in the growth and development of plants, including spinach, where different light qualities can influence its morpho-physiological traits and overall quality. To explore this, an experiment was conducted, using three distinct LED lighting sets for spinach cultivation. Light 1 emphasized blue light, Light 2 served as the standard white light control, and Light 3 focused more on red light with occasional brief UV-C flashes. Additionally, mild water deprivation was induced using 2.5% polyethylene glycol (PEG). The results revealed that using a high red-to-blue light ratio with intermittent UV-C radiation significantly reduced various growth parameters of spinach, such as root length, shoot length, root volume, fresh and dry root and shoot weight, as well as total and relative chlorophyll contents, when compared to the control group. Furthermore, water deprivation had a negative impact on spinach's growth, affecting shoot and root length, and fresh and dry weight in all light qualities, proving to be fatal under Light 3 conditions. Therefore, it is essential to carefully select appropriate light qualities throughout the plant's life cycle to enhance the quality of spinach, especially when mild water deprivation is involved. Opting for a higher blue-to-red light ratio was found to be somewhat beneficial in improving the overall quality of spinach.

Keywords: abiotic stress; green leafy vegetables; light quality; pigments; water deprivation

Introduction

Spinach (*Spinacia oleracea* L. cv. 'Matador') is one of the economic vegetables with a minimum growth cycle and is grown annually (Ribera *et al.*, 2020). The increasing consumption of fresh (in salads) and processed spinach demonstrates its rising popularity worldwide. When fresh, steamed or barely cooked, spinach has a high biological value and is particularly abundant in antioxidants (Ribera *et al.*, 2020). It has high levels of fibers, minerals (Mn, Fe, K, Mg, Ca, Se), and vitamins (A, E, K, C, B2, B6, B9, folic acid) (Roberts and Moreau, 2016). Spinach is also known for its anti-inflammatory, antitumoral, anti-obesity and lipid-lowering effects. Consuming more antioxidant-rich fruits and vegetables, like spinach, may halt the deterioration of antioxidant defense mechanisms that occur with ageing (Hassan *et al.*, 2022). Spinach crops must be improved in quality

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and yield by finding new approaches. Moreover, efforts to reduce the potential environmental impact on the production and consumption of spinach are essential.

Severe abiotic stresses, such as drought stress, can negatively affect plant growth. However, mild stress can be intentionally induced to enhance antioxidant compounds without negatively impacting productivity in the edible part of the plant and promote plant adaptation to stressful conditions (Cogo *et al.*, 2011; Paim *et al.*, 2020). Additionally, there is evidence that plants subjected to minor abiotic stressors are more resilient to subsequent stresses such as those brought on by the postharvest storage procedure. The metabolic memory created by the original stimulation would be the reason for this effect (Paim *et al.*, 2020). Priming is the deliberate application of mild stresses to withstand stress in the future (Sorrentino *et al.*, 2020). The development of technical approaches to lower water resource use in food production has therefore been the subject of several initiatives (Akıncı and Lösel, 2012). So, the application of modest water deprivation may be worthwhile to stimulate the metabolic memory to withstand resilient conditions in the future. Spinach quality may be improved by mild water deprivation through a number of physiological and biochemical processes. Spinach plants adapt in ways that enhance their nutritional value, flavor, and general quality when they experience a minor water shortage. Here are several instances of how mild drought stress may affect spinach quality, mild water deprivation can lead to increased antioxidant content, enhanced phytochemical content, increased mineral uptake, improved leaf texture and taste, and changes in leaf morphology and composition. Antioxidants help plants cope with oxidative stress and can have positive effects on human health when consumed (Barros *et al.*, 2016).

Among various environmental factors, light is one of the most significant abiotic factors that regulate plant growth, photosynthesis, survival, and adaptation. Light quality affects plant development, photomorphogenesis, and tissue composition; in addition to light quantity, factors like intensity and length (photoperiod) also influence plant productivity (Ouzounis *et al.*, 2015). Red and blue light, for instance, are the colors most effectively used for photosynthesis, and red light promotes the development of the photosynthetic apparatus (Paradiso *et al.*, 2011). Far-red light encourages blooming in long-day plants, whereas blue light impacts stomatal opening, plant height, and chlorophyll biosynthesis. The red/far red ratio controls stem and branching length, leaf area, and reproduction (Zheng *et al.*, 2019). Seedlings grown under a combination of green, red, and blue lights were taller than those grown under monochromatic red or blue lights in *Arabidopsis thaliana* (Folta, 2004) and increased fresh and dry weight of tomato plant and fruit in combination with red and blue light is recorded (Kaiser *et al.*, 2019). By raising the expression of synthesis pathway genes, blue and UV wavelengths have been demonstrated to promote the accumulation of bioactive chemicals in plant tissues (Hasan and Bae, 2017). Bian et al. (2014) highlighted the positive effects of blue, UV-A, and UV-B on the formation of phenolic compounds in general and anthocyanins, as well as the positive impacts of blue, red, and UV-B on carotenoids in a variety of vegetables. Researchers have shown that UV-C-induced effects generally depend on radiation dose and developmental stage (Poiroux *et al.*, 2010). There is mounting evidence that plants may benefit from UV-C light (Urban *et al.*, 2016). These may result in changes to various primary and secondary metabolites, such as chlorophyll, carotenoids, phenolics, and glucosinolates (Katerova *et al.*, 2012; Vandenbussche *et al.*, 2018; Mewis *et al.*, 2012; Heinze *et al.*, 2018). When exposed to UV radiation, flavonoid accumulation was seen in epidermal cells, leaf hairs, and leaf wax (Harborne and Williams, 2000). UV light greatly stimulates the production of carotenoids such as violaxanthin, neoxanthin, antheraxanthin, luteoxanthin, and lutein (Molnar *et al.*, 2009). Exposure to UV-C radiation increased carotenoids in tomatoes (Bravo *et al.*, 2013). So, it becomes crucial to know what light quality leads to which response in plants. During the daytime, sunlight is the only source of different light qualities, but plants do not need all of them for proper growth. We need to understand and find what kinds of light in plants lead to the proper growth, leaf extension or stem elongation and yield. In greenhouse horticulture, this information could be used to improve crop yield, quality, and production schedules (Paradiso and Proietti, 2022).

The employment of advanced plant cultivation technologies in a controlled environment to assure good crop yield, even in the face of harsh external conditions or in high-density cultivation systems, has become more common in modern agriculture. Although some previous research was carried out to investigate the response of spinach to drought stress (Gilani *et al*., 2020) and light intensity (Nguyen *et al*., 2022), to our knowledge no research focused on whether different light qualities and mild water deprivation can affect the morpho-physiology of spinach plants. The present experiment was carried out to study how different qualities of light influenced the growth parameters (root and shoot length, fresh and dry root and shoot weight, root volume), photosynthetic pigments and MDA content of spinach in general and in combination with mild water deprivation.

Materials and Methods

Experimental location and conditions

The Department of Applied Plant Biology, Institute of Crop Sciences, University of Debrecen, Hungary, conducted this experiment in 2021. Garafarm Trade Kft. in Budapest provided the spinach seeds, which were surface sterilized with 6% [v/v] H_2O_2 for 20 minutes before being properly washed and rinsed with deionized water. Three replicates of the 2.5% concentration PEG 6000 solution (VWR International bvba Geldenaaksebaan, Leuven, Belgium) were utilized to compare it to the control treatment, which only employed the nutritional solution. The nutrient mixture included 0.7 mM K_2SO_4, 0.5 mM $MgSO_4$, 0.1 mM KH_2PO_4, 0.1 mM KCl, 0.5 µM $MnSO_4$, 0.5 µM $ZnSO_4$, 10 µM H_3BO_3, and 0.2 µM $CuSO_4$ along with 2.0 mM Ca $(NO_3)_2$. Additionally, iron was given in the form of 10^{-4} M Fe-EDTA (Marschner *et al*., 1990). The seeds were grown geotropically at 24 °C between moist filter sheets. The humidity was preserved at 62.5%± 0.5% while the room temperature was maintained at 24 °C ± 0.2 °C. After they developed two true leaves, seedlings of the same size were transplanted into plastic pots (1.7 liters) in a hydroponic environment. The racks on which pots were placed were equipped with LED lamp sets (Tungsram Ltd, Hungary) with 300 µmol m^{-2} s^{-1} and three different light qualities, Light 1 with higher percentage of blue light (Blue >>Red), Light 2 with normal white light taken as control and Light 3 with higher red light (Red > Blue >) along with flashes of UV-C once a week (Table 1).

Table 1. Percentage of different light qualities used in the experiment

LED Lamps	Light quality						
	Blue	Green	Red	Far-red	UV-C	Total PPF	Explanation
Light 1	20%	40%	66%	10%	0%	245 µmol/s	Blue >>Red
Light 2	35%	48%	15%	1%	0%	350 µmol/s	Normal White
Light 3	12%	4%	75%	10%	1%	308 µmol/s	Red > Blue > Flashes of UV-C radiations once a week for 5 minutes.

In the experiment, six pots were set up for each LED lamp set, with each pot containing four spinach plants. Among these pots, three were filled with a nutrient solution, and the other three were filled with a nutrient solution mixed with 2.5% polyethylene glycol (PEG) to induce mild water deprivation.

Throughout the experiment, the nutrient solution was replaced every three days until harvest. On the 25th day after sowing, two plants were harvested from each pot containing only the nutrient solution to examine the impact of various light qualities on spinach growth.

For further investigation, the remaining two plants from each pot (with only nutrient solution) were allowed to grow until the 35th day after sowing, serving as the control group to compare against the plants grown with the nutrient solution mixed with 2.5% PEG under different light qualities. These plants were harvested on the 35th day (Full harvest) to analyze the effects of mild drought and different light qualities on spinach growth and development.

Growth parameters

Measurements were taken from three replicates to determine the length of roots and shoots. The first measurement was conducted on the 25th day after sowing, referred to as the first harvest, while the second measurement was taken on the 35th day after sowing, named as the full harvest. Root and shoot lengths in three replicates were measured using a ruler after both harvests. To assess the volume of the roots, the water displacement technique was employed, whereby the sample volume was determined by calculating the difference between the initial and final water levels. Fresh weights of both roots and shoots were measured using an electronic scale manufactured by Ohaus in Switzerland. To obtain the dry weights, three replicate samples from each treatment were dried in an oven set at 70 °C for four days, until a consistent weight was achieved.

Relative chlorophyll content

SPAD values were recorded using a SPAD-502Plus device manufactured by Konica Minolta in Japan to assess the relative chlorophyll content. Measurements were taken every other day over a period of ten days during the first harvest, and at two-day intervals during the full harvest. Three repetitions were performed for each treatment, with replicates taken from fully-grown leaves.

Total chlorophyll content (Chl-$_a$, Chl-$_b$) and total carotenoids (Chl$_{x+c}$)

Fresh leaf disks (0.05 g) were collected and transferred into plastic vials containing 5ml of N, N-Dimethylformamide for extraction of chlorophyll and carotenoids (Moran and Porath, 1980) and placed in the dark at 4 °C for three days. Chlorophyll and total carotenoid concentration in the extract was measured with V–VIS spectrophotometry (Metertech SP-830 PLUS, Taiwan) at three wavelengths; 480, 647 and 664 nm (Wellburn, 1994).

Malondialdehyde (MDA) Content

Trichloroacetic acid (TCA) was used as an extraction buffer to assess the MDA content of the lyophilized leaf samples (Christ, Germany) (Baryla *et al.*, 2000). 0.1 g of crushed leaf powder was homogenized in 1 ml of 0.1% (w/v) TCA. Following homogenization, the samples were centrifuged at 10,000 rpm for 10 min. and the supernatant was transferred to a tube containing 4 ml of 20% TCA and 0.5% thiobarbituric acid (TBA). The resulting mixture was heated for 30 min. at 95 °C before being promptly cooled on ice. The recovered material was centrifuged again at 10,000 rpm for 5 min. Absorbance was determined using a spectrophotometer at 532 nm (Metertech SP-830 PLUS, Taiwan) (Baryla *et al.*, 2000).

Antheraxanthin, lutein, and violaxanthin content

To 0.05 g of leaf powder, 1.5 ml of 80% acetone was added and stored inside the fridge (4 °C) for one day. Samples were centrifuged for 10 min. at 13000 rpm, and the supernatant was separated from the pellet. The supernatant was stored inside the fridge (4 °C), and 1 ml of 80% acetone was added to the pellet and stored in the fridge (4 °C) for one day. Again, the samples were centrifuged at 13000 rpm for 10 min. Supernatants obtained were mixed and the pellet was discarded. The method used to determine the Antheraxanthin, Lutein, and Violaxanthin content in the extract was HPLC (ABL$^{\&}$E-Jasco Hungary Ltd.) (Goodwin *et al.*, 1988), specifically using a Nucleosil C18 column. The eluents used were acetonitrile and water in a 9:1 ratio, with 0.01% triethylamine, as well as ethyl acetate. The HPLC-system used for the analysis was equipped with a UV/VIS detector manufactured by JASCO in Japan. To identify peaks in the chromatogram and calculate pigment contents, zeaxanthin was regularly injected as a standard compound during the analyses (Toth *et al.*, 2002).

Experimental design and statistical analysis

A randomized complete block design with three replications and four plants per replica was used to arrange the pots. Analysis of variance (ANOVA) and the Tukey Post Hoc test was used by the SPSS program (Version 26, IBM, USA) to indicate the significantly different means of each treatment.

Results

Effect of different light qualities on the morpho-physiology of spinach

Growth parameters

The growth parameters of spinach (root and shoot length, root volume, fresh and dry mass of root and shoot) were observed to decrease significantly when exposed to Light 3 compared to both Light 2 and Light 1 at both harvest times, as presented in Table 2.

At the first harvest, compared to the control group (Light 2), significant reductions were recorded under Light 3: 48.8% decrease in root length, 73.6% decrease in shoot length, 93.8% decrease in root volume, 95.7% decrease in fresh root weight, 93.5% decrease in fresh shoot weight, 93.7% decrease in dry root weight, and 91.6% decrease in dry shoot weight.

At the full harvest, under Light 3 compared to Light 2, there was a significant decrease in shoot length by 32.0%, fresh root weight by 84.4%, and fresh shoot weight by 71.2%. However, root length increased by 9.5%, and there were decreases in root volume by 55.2%, dry root weight by 9.2%, and dry shoot weight by 28.7%.

Under Light 1, compared to Light 2 (control), there was a significant decrease in root length by 25.9% at the first harvest. However, at the full harvest, there was a significant increase in root volume by 91.7% and fresh root weight by 37.5%.

Furthermore, under Light 1 compared to Light 2, at the first harvest, there was an increase in shoot length by 4.0%, root volume by 6.6%, fresh root weight by 17.6%, fresh shoot weight by 16.7%, and dry root weight by 130%. At the full harvest, there was a decrease in shoot length by 9.7%, an increase in fresh shoot weight by 5.13%, and an increase in dry root weight by 18.3%.

In summary, Light 3 negatively impacted the growth parameters of spinach the most, while Light 1 showed some positive effects on certain growth aspects at both harvest times when compared to the control group (Light 2).

Table 2. Root length (cm), shoot length (cm), root volume (ml), fresh root and shoot, dry root, and shoot weight (g) under different light qualities

	First Harvest (25th day after sowing)			Full Harvest (35th day after sowing)		
Trait	Light 1 (Blue >>Red)	Light 2 (Normal White)	Light 3 (Red > Blue > Flashes of UV-C radiations once a week for 5 minutes)	Light 1 (Blue >>Red)	Light 2 (Normal White)	Light 3 (Red > Blue > Flashes of UV-C radiations once a week for 5 minutes)
Root Length (cm)	33.8^{B}	45.6^{A}	23.3^{B}	30.4^{A}	35.7^{A}	39.1^{A}
Shoot Length (cm)	12.9^{A}	12.4^{A}	3.2^{B}	15.7^{A}	17.4^{A}	11.8^{B}
Root volume (ml)	6.58^{A}	6.1^{A}	0.3^{B}	33.6^{A}	17.5^{B}	7.8^{A}
Fresh root weight (g)	5.26^{A}	4.4^{A}	0.19^{B}	29.4^{A}	21.4^{B}	3.3^{C}
Fresh shoot weight (g)	6.77^{A}	5.8^{A}	0.38^{B}	20.5^{A}	19.5^{A}	5.6^{B}
Dry root weight (g)	0.23^{A}	0.1^{A}	0.01^{B}	0.71^{A}	0.6^{A}	0.5^{A}
Dry shoot weight (g)	0.60^{A}	0.4^{B}	0.04^{C}	1.83^{A}	1.9^{A}	1.36^{A}

*Note: Different letters among light qualities within a specific harvest indicate significant differences ($p \leq 0.05$).

Relative chlorophyll content

Relative chlorophyll content (SPAD values) significantly decreased by 44.5, 38.5, 25.5, 30.6, and 22.0% in Light 3 compared to Light 2 respectively, on each day of measurement. Under Light 1, it first decreased by 0.9 and 7.9% (Figure 1) on the first and second days of measurement, later significantly increased by 12.8 and 25.8% on the fourth and fifth day of measurement compared to Light 2.

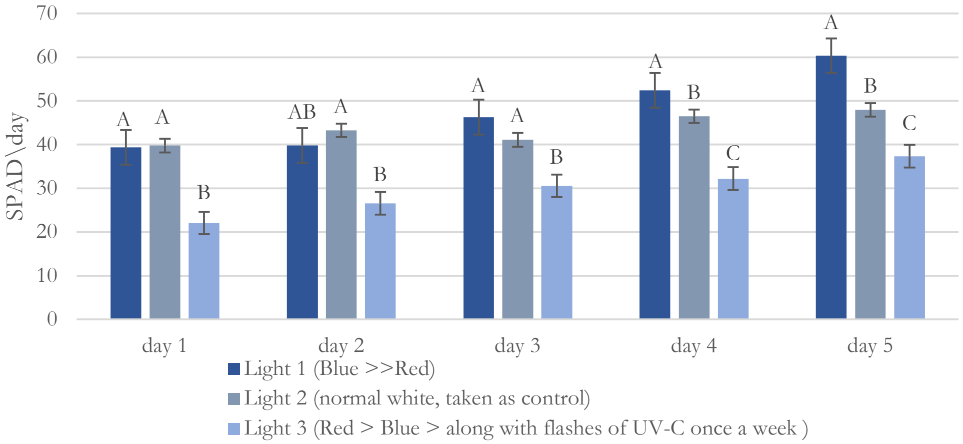

Figure 1. Relative chlorophyll content (SPAD) during five days under different light qualities (First harvest)

*Note: Different letters in each day correspond to significant differences among treatments ($p \leq 0.05$). n=3, ± S.E.

Contents of photosynthetic pigments

Chlorophyll-a *(Chl-*$_a$*)* significantly decreased by 49.4% under Light 3 and increased by 12.0% under Light 1 compared to Light 2. Chlorophyll- b, also significantly decreased by 56.8% under Light 3 and increased by 25.7% under Light 1 compared to Light 2. Similarly, total carotenoids significantly decreased by 47.1% under Light 3 and increased by 18.1% under Light 1 compared to Light 2 (Figure 2).

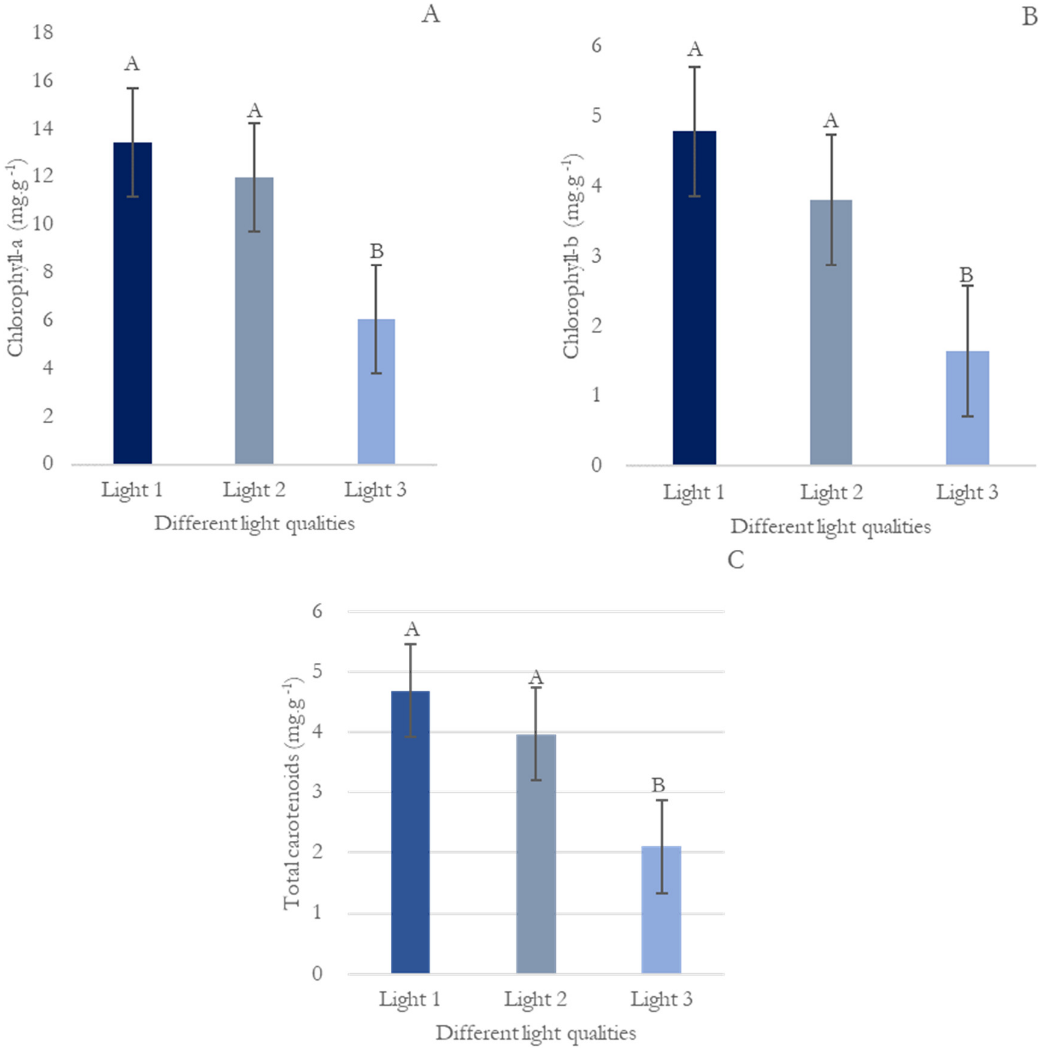

Figure 2. Contents of photosynthetic pigments [chlorophyll- a (A), chlorophyll-b (B) and total carotenoids (C) (mg. g^{-1})] in spinach leaves grown under different light qualities provided by LED Lamps
*Note: Different letters correspond to significant differences ($p \leq 0.05$) among lights in a particular trait. n=3, ± S.E.

Contents of different carotenoids (antheraxanthin, lutein, violaxanthin)

Under Light 3, antheraxanthin increased by 24.8%, while in Light 1, it decreased by 24.5% compared to Light 2. Lutein increased by 1.32% under Light 3 and 43.4% under Light 1 compared to Light 2. Similarly, violaxanthin increased by 1.9% under Light 3 and 16.4% under Light 1 compared to Light 2 (Table 3).

Table 3. Contents of different carotenoids [antheraxanthin, lutein, and violaxanthin (μg μL^{-1})] and MDA (nmol g^{-1}) under different light qualities

Trait	Light 1	Light 2	Light 3
Antheraxanthin (μg μL^{-1})	3.19^{A}	4.23^{A}	5.2^{A}
Lutein (μg μL^{-1})	136.2^{A}	94.9^{A}	96.2^{A}
Violaxanthin (μg μL^{-1})	57.0^{A}	49.0^{A}	49.0^{A}
Malondialdehyde (nmolg^{-1})	11.9^{A}	13.2^{A}	13.3^{A}

*Note: Different letters correspond to significant differences ($p \leq 0.05$).

Malondialdehyde content

The MDA levels in nmol g^{-1} increased from 11.9 under Light 1 to 13.3 in Light 3, indicating an increase of 11.2%. Similarly, under Light 2, the MDA levels increased to 13.2 $nmolg^{-1}$, which is a 10.4% increase compared to Light 1 (Table 3).

Effect of mild drought stress at different light qualities (Full harvest)

Growth parameters

In the presence of 2.5% PEG under Light 1, the following parameters were significantly decreased compared to the control of Light 1: root length by 36.15%, shoot length by 72.2%, root volume by 53.1%, fresh root weight by 97.5%, fresh shoot weight by 97.7%, dry root weight by 95.6%, and dry shoot weight by 91.6%. Similarly, under Light 2, treatment with 2.5% PEG resulted in a significant decrease in the following parameters compared to the control of Light 2: root length by 53.2%, shoot length by 52.3%, root volume by 94%, fresh root weight by 90%, fresh shoot weight by 89.7%, dry root weight by 81.2%, and dry shoot weight by 68.7% (Table 4).

Under Light 3, when exposed to flashes of UV-C radiation and treated with PEG, the plants could not survive. Compared to the PEG treatment of Light 1, it was recorded that root length decreased by 1.25% and root volume decreased by 87.9% under the PEG treatment of Light 2. However, shoot length increased by 65.6%, fresh root weight increased by 238%, fresh shoot weight increased by 300%, and dry root and shoot weight increased by 200% under Light 2 compared to Light 1 (Table 4).

Table 4. Root length(cm), shoot length(cm), root volume (ml), fresh root and shoot weight, dry root and shoot weight (g), SPAD value per day and MDA (nmol g^{-1}) after mild water deprivation under two different light qualities

Trait	Light 1		Light 2	
	Control	2.5% PEG	Control	2.5% PEG
Root length (cm)	$33.83^{B,1}$	$21.60^{A,2}$	$45.67^{A,1}$	$21.33^{A,2}$
Shoot length (cm)	$12.92^{A,1}$	$3.58^{B,2}$	$12.42^{A,1}$	$5.92^{B,2}$
Root volume (ml)	$6.58^{A,1}$	$3.08^{A,2}$	$6.17^{A,1}$	$0.37^{A,2}$
Fresh root weight (g)	$5.26^{A,1}$	$0.13^{A,2}$	$4.47^{A,1}$	$0.44^{A,2}$
Fresh shoot weight (g)	$6.77^{A,1}$	$0.15^{A,2}$	$5.88^{A,1}$	$0.60^{A,2}$
Dry root weight (g)	$0.23^{A,1}$	$0.01^{A,2}$	$0.16^{A,1}$	$0.03^{A,2}$
Dry shoot weight (g)	$0.60^{A,1}$	$0.05^{A,2}$	$0.48^{B,1}$	$0.15^{A,2}$
SPAD day 1	$39.4^{A,1}$	$21.2^{A,1}$	$39.7^{A,1}$	$41.9^{A,1}$
SPAD day 2	$39.8^{A,1}$	$14.6^{B,2}$	$43.2^{A,1}$	$39.3^{A,1}$
Malondialdehyde ($nmolg^{-1}$)	$13.20^{A,1}$	$16.22^{A,1}$	$11.95^{A,1}$	$16.41^{A,2}$

*Note: Different letters indicate the significant difference at $p \leq 0.05$ within treatments in a different light and the different numbers indicate the significant difference at $p \leq 0.05$ within treatments in a particular light.

Relative chlorophyll content

When treated with 2.5% PEG under Light 1, the SPAD value decreased by 46% and 63.3% (measured at 2-day intervals) compared to control. In contrast, under Light 2, there was an initial increase of 5.5% in SPAD value, followed by a decrease of 8.9%. In PEG treatment under Light 2, an increase of 97.6% compared to PEG treatment of Light 1 on the first day and 69% on day 2 was recorded (Table 4).

Malondialdehyde (MDA) content

In the presence of 2.5% PEG under Light 1, the MDA levels increased from 13.2 to 16.2 nmol/g, indicating an increase of 22.8% compared to control. Similarly, under Light 2, the MDA levels increased from 11.9 to 16.4 nmol/g, indicating an increase of 37.3% when treated with 2.5% PEG. However, on comparing with light + PEG treatment, under light 2, 1.8% increase was recorded compared to Light 1 (Table 4).

Discussion

Light and water are two crucial needs of plants regulating their survival, morpho-physiology, and productivity (McElrone *et al.*, 2013; Bayat *et al.*, 2018; Klem *et al.*, 2019), and abundance or scarcity of any of them imposes deleterious effects on plants and limit crop productivity (Fahad *et al.*, 2017). In nature, plants are exposed to a combination of stresses, and their impact differs from the individual impact of stress (Francini and Sebastiani, 2019). Combinatorial stresses may be antagonistic or synergistic to each other. For instance, heat and drought stress acts synergistically and cause more damage than their individual treatments (Pandey *et al.*, 2017). In contrast, some stresses in combination (drought and ozone, drought, and pathogen) act antagonistically. Some stress combinations have a net neutral or beneficial effect on plants because they cancel out one another (Pandey *et al.*, 2017). In our results the combination of mild water deprivation and flashes of UV-C acted synergistically and proved fatal to spinach. Yield is not always negatively impacted since one stress may give rise to another's resistance.

Individual drought and ozone stresses hinder the growth of *Medicago truncatula* (alfalfa), but the two together boost the plant's ability to withstand the combined stress (Puckette *et al.*, 2007). The present study showed a differential response of spinach exposed to different light qualities and the response of spinach under mild water deprivation in different light qualities. Both light (quality and quantity) and drought induce various physiological, molecular, and biochemical responses in plants, thereby inducing the generation of active oxygen species (AOS), resulting in oxidative damage at the cellular level (Katerova *et al.*, 2017; Mewis *et al.*, 2012; Foyer and Noctor, 2002; Czeczuga, 1987; Muraoka *et al.*, 2002).

Plant growth is a complex process that can be significantly influenced by various environmental factors, including the quality and quantity of light. These factors play a crucial role in determining the growth characteristics of plants, such as root and shoot length, root volume, fresh root and shoot weight, as well as dry root and shoot weight. When plants are subjected to unfavorable light conditions, such as insufficient or poor-quality light, their growth is adversely affected. In the present experiment, growth parameters (root and shoot length, root volume, fresh root and shoot weight, dry root and shoot weight) were affected in plants raised under different light qualities, and maximum reduction was observed in Light 3 (Red > Blue > along with flashes of UV-C once a week) compared to Light 2 (Red > Blue > taken as control) and Light 1 (Blue >>Red) (Table 2). The reduction could be due to oxidative stress generated by a higher accumulation of AOS and MDA content, leading to a decline in chlorophyll content (Figure 2) and consequently decreasing the growth in stressed plants. Moreover, UV-C light has also been shown to be harmful to chloroplasts, mitochondria, and, more broadly, membranes in higher plants. Starting with chloroplasts, UV-C light has been shown to directly destroy plastoquinone (Shavit and Avron, 1963). According to Wituszynska *et al.* (2014), UV-C radiation damages the chloroplasts in *Arabidopsis thaliana* and causes morphological alterations in mesophyll cells that mimic apoptosis. UV radiation degrades the endogenous Phytohormones such as auxin levels, thus inferring normal growth and developmental processes in plants (Vandenbussche *et al.*, 2014). Similar results were recorded in *Vigna unguiculata* L. (Lingakumar and Kulandaivelu, 1993) and *Beta vulgaris* L. (Panagopoulos *et al.*, 1990). UV exposure also interferes with various critical physiological processes associated with biomass production, thus reducing the growth and biomass of crop plants, as observed in lettuce (Paul *et al.*, 2012), rice (Hidema *et al.*, 2005), wheat and sorghum (Kataria and Guruprasad, 2012). Plant height reduction in vegetables was also recorded earlier (Ruhland *et al.*, 2007; Singh *et al.*, 2011; Kataria *et al.*, 2013; Baroniya *et al.*, 2014; Zhang *et al.*, 2014). UV-induced plant height reductions are more or less due to the direct damage to macromolecules such as DNA (Britt, 1999) and proteins (Gerhardt *et al.*, 1999). UV exposure consequently leads to changes in the morphology and growth, e.g., smaller but thicker leaves, less plant height and lower biomass (Suchar and Robberecht, 2015). This may be the reason that in present experiment plants could not survive under combinatorial stress of drought and UV-C radiation.

In our experiment, the presence of 2.5% PEG (Polyethylene Glycol) under different light conditions (Light 1, Light 2, and Light 3) has been investigated. The results indicate that under Light 1, the parameters related to plant growth, including root length, shoot length, root volume, fresh root weight, fresh shoot weight, dry root weight, and dry shoot weight, showed a significant decrease compared to the control. Similarly, under Light 2, the same growth characteristics exhibited a significant decrease when plants were treated with 2.5% PEG. These findings suggest that in both light conditions, the presence of PEG negatively impacts plant growth, resulting in reduced root and shoot length, decreased root volume, as well as lower fresh and dry root and shoot weights. Moreover, under Light 3, the combination of flashes of UV-C radiation and PEG treatment proved to be detrimental to plant survival. Under different light qualities (Light 1 and Light 2), and mild drought along the growth traits, relative chlorophyll content decreased compared to the control (Table 4). According to Qaderi et al. (2007), drought stress may cause stunted growth as a result of decreased cell wall flexibility and turgor, changes in plant architecture that result in decreased height, smaller leaves, fewer leaves, decreased leaf water potential, turgor pressure, stomatal closure, and reduced cell growth and expansion. Other crucial physiological mechanisms, including the production of chlorophyll, photosynthesis, respiration, nutrition, and carbohydrate metabolism, are all impacted by drought stress (Jaleel *et al.*, 2008; Farooq *et al.*, 2009; Li *et al.*, 2011). Overall, these findings highlight the sensitivity of plant growth to environmental factors, particularly light quality, and quantity, as well as the impact of PEG treatment. Understanding these relationships can provide valuable insights into optimizing plant growth conditions and mitigating the negative effects of environmental stressors on plant development.

Light for photosynthesis is pursued by the protein pigment complexes, chlorophylls and carotenoids (Jahns and Holzwarth, 2012). Thus, it is a crucial factor in assessing the plant under different stresses (Habiba *et al.*, 2014). In the present experiment, the levels of total chlorophyll content, chlorophyll a and chlorophyll b and SPAD significantly decreased in plants grown under different light qualities and highest reduction was observed in Light 3 compared to Light 2 and Light 1. The decrease in chlorophyll levels can be attributed to the suppression of chlorophyll production or the breakdown of the pigment along with its precursors, protochlorophyll and protochlorophyllide (Santos *et al.*, 2004; Teramura, 1983; Teramura, 1994). The outcomes of our study are consistent with previous findings reported in various plants such as grape vines (Martinez *et al.*, 2013), soybean (Ambasht and Agarwal, 2003), okra (Kumari *et al.*, 2009), sweet wormwood (Rai *et al.*, 2011), Swedish ivy (Vidovic *et al.*, 2014), cotton, sorghum, wheat (Kataria and Guruprasad, 2007), pea (Singh *et al.*, 2015), basil (Sakalauskaite *et al.*, 2012), common privet (Guidi *et al.*, 2016), canola (Tohidi *et al.*, 2011), maize (Gao *et al.*, 2004), and barley (Palmer *et al.*, 2002). Nonetheless, the impact was more harmful when plants were subjected to a combination of UV-C light and drought stress. The results align with Nyachiro et al. (2001), who reported a decrease in chlorophyll content caused by drought stress in *Triticum aestivum*. Reducing total chlorophyll under drought stress suggests a reduced capacity for light-harvesting complexes (Teramura, 1983; Teramura, 1994; Santos *et al.*, 2004).

Carotenoids and xanthophylls are essential to light-dependent processes, photoprotection, and potent free radical scavengers (Jahns and Holzwarth, 2012). According to North et al. (2007), carotenoids play a significant role in responding to stress. They act as excellent scavengers of AOS (active oxygen species) and are crucial for defending plants against light stress. Carotenoids protect chlorophylls from photooxidative damage resulting from UV irradiation by dissipating excess excitation energy. In the current study, the level of Carotenoids content (antheraxanthin, lutein and violaxanthin) increased under stress conditions, and the maximum was observed in plants raised under Light 3 (Table 3). In agreement with our results, Molnár et al. (2009) observed an increase in carotenoids, namely violaxanthin, luteoxanthin, neoxanthin, antheraxanthin, and lutein, in plants exposed to stress conditions. An increase in carotenoid content represents a biochemical response to alleviate UV stress (Palmer *et al.*, 2002), as observed in maize (Ambasht and Agrawal, 1998) and pea (Singh *et al.*, 2015). UV radiation in higher plants can trigger the rise in carotenes. An increase in antheraxanthin and zeaxanthin, along with a decrease in other carotenoids, was recorded in Swedish Ivy on

UV-B treatment (Vidovic *et al.*, 2014). Lutein decreased in red lettuce after UV-B treatment (Caldwell and Britz, 2006).

The primary target of most stresses is the cellular membranes that endure lipid peroxidation induced by excessive accumulation of AOS, resulting in excess production of MDA, which indicates stress injury (Martinez *et al.*, 2013). AOS production, lipid peroxidation, and membrane damage are known effects of UV-C radiation (Hideg and Vass, 1996; Takeuchu *et al.*, 1996). Lipid peroxidation of a membrane can be directly predicted by MDA content (Health and Packer, 1968) and MDA increase under stress conditions (Lei *et al.*, 2007). In the present study, higher MDA content was observed in plants raised under Light 3, and the effect was synergistic in the case of a combination of different lights and water deprivation. Higher accumulation of MDA indicates more lipid peroxidation in the cell membrane and consequently will lead to cell death. Similar results were also observed in rice (Zhou *et al.*, 2007), *Withania somnifera* (Takshak and Agarwal, 2014), and *Ditylum brightwellii* (Rijstenbil, 2001).

Conclusions

This study emphasizes the significance of blue light in plant growth and the influence of varied light qualities on several aspects of plant development. The presence or absence of blue light may impact root and shoot length, fresh and dry weight, root volume, chlorophyll, carotenoid content, and malondialdehyde (MDA) levels. According to the study, when using LED technology, spinach develops better when exposed to more blue light than red light. UV-C rays, on the other hand, may harm plants, especially when combined with water deprivation. It was found that under such circumstances, mild water stress does not have any beneficial impacts on the development and quality of spinach. The correct UV-C treatment may increase the carotenoid content of spinach, but determining the appropriate doses and knowing how it interacts with the environment will be challenging problems to solve in the future. The findings emphasize the need to consider UV-C radiation and the light spectrum when designing lighting systems for indoor plant growth.

Authors' Contributions

Conceptualization, S.V.; methodology, S.V.; software, O.B.; validation, S.V., O.B. and T.B.Z.; formal analysis, O.B.; investigation, T.B.Z..; resources, S.V.; data curation, S.V.; writing—original draft preparation, T.B.Z. and S.V..; writing—review and editing, O.B. and S.V.; visualization, O.B.; supervision, S.V.; project administration, S.V.; funding acquisition, S.V. All authors have read and agreed to the published version of the manuscript.

Ethical approval (for researches involving animals or humans)

Not applicable.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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