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RESEARCH ARTICLE

Red light in addition to white light improve commercial characteristics and yield of purple cabbage microgreens

Arthur Bernardes Cecílio Filho[1*], Maria José Yañez Medelo[1], Wellington Missiano Pindobera[1], Thatiane Nepomuceno Alves[1], Laura Matos Ribera[1], Rogério Falleiros Carvalho[2], Lucas Natan Camacho da Silva[1], Manuela Oliveira de Souza[3], and Luis Felipe Villani Purquerio[4]

[1]Universidade Estadual Paulista (Unesp), Departamento Produção Vegetal, Jaboticabal, Brazil.
[2]Universidade Estadual Paulista (Unesp), Departamento de Biologia, Jaboticabal, Brazil.
[3]Universidade Federal do Recôncavo da Bahia (UFRB), Centro de Ciências Exatas e Tecnológicas, Cruz das Almas, Brazil.
[4]Instituto Agronômico de Campinas, Campinas, Brazil.
[*]Corresponding author (arthur.cecilio@unesp.br)
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ABSTRACT

White light has been used in plant factories due to its broad light spectrum, which has positive effects on photosynthesis and photomorphogenesis, lower LED costs, and greater comfort for workers' eyes. However, it is also known that higher proportions of red light can have a positive effect on growth and, consequently, productivity. So, an experiment was carried out in plant factory conditions with the hypothesis that the addition of low-intensity red to white light can increase yield of the purple cabbage (*Brassica oleracea* L. var. *capitata* L.) microgreens. The experimental design was completely randomized, in a 2 × 3 + 1 factorial scheme, where the photosynthetic photon flux density (PPFD, 20 and 40 µmol m^{-2} s^{-1}) and photoperiod (12, 16, 20 h d^{-1}) of red light were evaluated in addition to white light at 250 µmol m^{-2} s^{-1} and 20 h (control treatment). Red light did not affect hypocotyl length, but photoperiod and PPFD affected cotyledon area and yield of microgreens separately. Photoperiod 16 h d^{-1} provided greater cotyledon area (+10.0%) and yield (+17.9%) than 12 h d^{-1} and did not differ from 20 h d^{-1}. Compared to microgreens that received only white light (control treatment), red light promoted 22.7% higher cotyledon area and microgreens irradiated with 40 µmol m^{-2} s^{-1} had greater cotyledon area (+7.0%) than those under 20 µmol m^{-2} s^{-1}, but without increasing yield. Therefore, it is recommended to grow purple cabbage microgreens with the addition of 20 µmol m^{-2} s^{-1} and 16 h d^{-1} red LED to white light (250 µmol m^{-2} s^{-1} and 20 h d^{-1}).

Key words: *Brassica oleracea* var. *capitata*, functional food, light spectrum, plant factory, urban farm.

INTRODUCTION

In the group of nutraceutical foods, microgreens have aroused the interest of the population as they constitute a new presentation of fresh vegetables, mainly because they have morphological and sensory characteristics, as well as high nutritional content with excellent benefits for human health (Guardiola-Márquez et al., 2023).

Plant factory has been an efficient and effective production system for microgreens, as it offers a reliable environment for having the production factors highly controlled. Among them, light has been the main target of research because the management of photosynthetically active photon flux density (PPFD), photoperiod and spectrum generate changes in morphology and growth (Turner et al., 2020). It has been reported that plants subjected to high intensity and/or long exposure to red light (monochromatic) have impaired growth, which is explained by the development of red-light syndrome, characterized by low photosynthetic capacity,

low N use efficiency, and absence of stomatal conductance response (Hogewoning et al., 2010; Trouwborst et al., 2016; Miao et al., 2019). Additionally, due to the broad spectrum of wavelengths, white light can positively impact physiological processes compared to monochromatic light or dichromatic compositions, as noted by Yang et al. (2018) and Nguyen et al. (2021). Bueno and Vendrame (2024) observed that white light was more effective for C fixation and plant growth than blue and red light alone or in combination. Mendes et al. (2024) and Medelo et al. (2025) obtained high yields of arugula (4.5 kg m^{-2}) and purple cabbage (8.2 kg m^{-2}), respectively, in cultivation with white light.

Notwithstanding the favorable condition for the production of microgreens with white LED, the possibility of increasing yield should always be sought in a cultivation environment such as that of plant factories, which allows the control of production factors. Our hypothesis is that purple cabbage microgreens will respond positively to the higher proportion of red light due to the addition of red LED to white LED, whose intensity and photoperiod of white light were optimized for the cultivation of purple cabbage microgreens in a study conducted by our research group and reported by Medelo et al. (2025). It is believed that the presence of the blue light wavelength in white light will attenuate red light syndrome, allowing for further growth of purple cabbage microgreens. Podsędek et al. (2023) recommend adding red light to white light in microgreens to increase the contents of phenolic compounds and anthocyanins compared to white light alone. However, the authors did not evaluate the effect on biometric parameters of purple cabbage microgreens, which are important commercial attributes and should be part of the evaluation of the use or not of the red-light addition.

No study was found on the effects of the addition of red light to white light on purple cabbage microgreens. Therefore, establishing adequate lighting protocols in plant factories is extremely important, since species may respond differently to PPFD and photoperiods. In view of the above, the objective of this study was to evaluate the effect of red light additional to white light on biometric parameters and yield of purple cabbage microgreens.

MATERIALS AND METHODS

Location and experimental period

From 10 to 18 May 2023, an experiment was carried out at the Plant Factory Laboratory, located at the São Paulo State University, in the city of Jaboticabal, Brazil. The temperature and relative humidity during the experiment ranged from 22 to 25 °C and 50% to 70%, respectively.

Characterization of the treatments and experimental design

In addition to 250 µmol m^{-2} s^{-1} and a photoperiod of 20 h d^{-1} white light irradiance (control, white LED), six treatments were evaluated in a factorial scheme (2 × 3 +1) namely: Photosynthetic photon flux density (PPFD, 20 and 40 µmol m^{-2} s^{-1}) and photoperiod (12, 16, 20 h d^{-1}) of red light (red LED). Both the white and red LEDs were turned on at the same time at 11:00 h. The white LED was turned off at 07:00 h, while the red LED followed the time determined in each treatment (12, 16 or 20 h). The irradiances were measured using a spectroradiometer (SpectraPen SN-SP-144, Photon Systems Instruments, Drásov, Czech Republic). The experimental design was completely randomized and treatments were replicated six times.

White LEDs, 7 W, 48 V, model GLFS-v.11.7.4.22 (LEDs-up, Botucatu, São Paulo, Brazil), composed of wavelengths in the blue (25.4%), green (23.8%), yellow/orange (21.3%), red (27.1%) and far red (2.3%) ranges were used. The red LEDs had 75.9% red, 11.0% far red, 1.3% yellow/orange, 0.2% green and 11.7% blue (Figure 1). According to the percentages of wavelengths present in the LEDs, the addition of 20 and 40 µmol m^{-2} s^{-1} in red LED increased the red:blue ratio from 1.15:1 in white LED to 1.38:1 and 1.59:1, respectively.

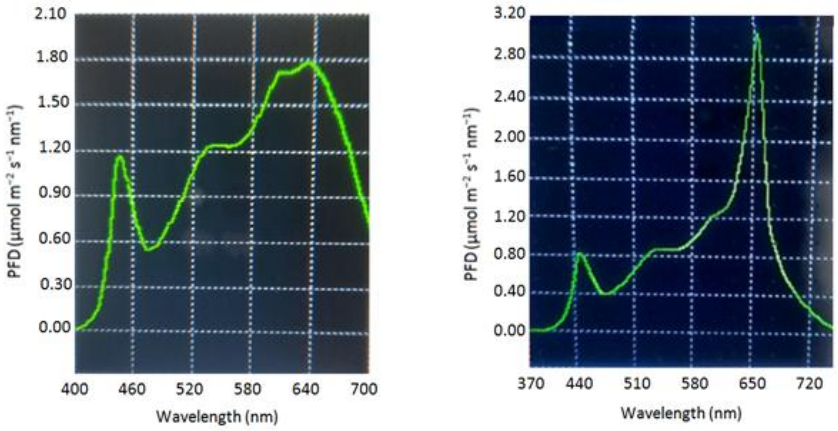

Figure 1. Photon flux density (PFD) per wavelength of the white LED (A) and red LED (B) used in the experiment.

Installation and conduction of the experiment

Rectangular polypropylene trays (20 × 13 × 4.5 cm), filled with 1.5 cm of Bioplant organomineral substrate for vegetables (pH 6 ± 0.3 and electrical conductivity of 0.8 dS m^{-1} ± 0.06; Bioplant Misturadora Agrícola Ltda., Nova Ponte, Minas Gerais, Brazil), were sown with 300 g m^{-2} red cabbage (*Brassica oleracea* L. var. *capitata* L.) 'Mamouth Red Rock' (Feltrim Sementes, Farroupilha, Rio Grande do Sul, Brazil), without incorporation of seeds. Substrate and seeds were sprayed with water, the trays were stacked and placed in the dark for 3 d, during which the seedlings germinated, took root, grew the hypocotyl and emitted the cotyledons. The trays were then transferred to the Plant Factory Laboratory, placed on shelves, with LEDs 0.27 m above from the cotyledons of the microgreens. The application of the treatments was then initiated.

The microgreens received a nutrient solution recommended with 174.0, 24.0, 39.0, 183.0, 142.0, 38.0, 52.0, 0.3, 0.02, 2.0, 0.4, 0.06 and 0.06 mg L^{-1} N-NO_3^-, N-NH_4^+, P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo and Zn, respectively. The nutrient solution was absorbed by the microgreens by capillarity, through 2 mm diameter holes, equidistant in 3 cm, present in the bottom of the tray. Once the nutrient solution provided to the tray had been absorbed, a new amount was applied. We will add this information to the manuscript. On the first day, 500 mL nutrient solution were made available, 250 mL on the following 3 d and 350 mL on the last day per tray. The microgreens were harvested 5 d (120 h) after the start of the application of red light, when the seedlings had fully expanded cotyledons, without the first leaf being visible.

Evaluated characteristics

From each experimental unit, 50 seedlings per tray were randomly cut at the level of the substrate. A graduated ruler was used to measure hypocotyl length (HL, cm). From the same 50 seedlings used to evaluate HL, cotyledon area (CA, cm^2 $microgreen^{-1}$) was evaluated using the electronic area meter LI 3100 (LI-COR, Tucson, Arizona, USA). The microgreens from a tray were harvested by cutting the hypocotyl close to the substrate and immediately weighed on a scale with 0.01 g precision to evaluate yield (g m^{-2}). On the day of harvest, a portable fluorometer (OS30p, Opti-Science, Hudson, Massachusetts, USA) was used to evaluate the quantum efficiency of photosystem II; for that, data of initial fluorescence (F_0), maximum fluorescence (F_m), variation in fluorescence calculated from F_0 and F_m (F_v) and maximum photochemical efficiency (F_v/F_m) were obtained 30 min after placing the clips.

Statistical analysis

The data for each characteristic were subjected to ANOVA (F test) and Tukey test to compare the means, using the AgroEstat (program v.1.1.0.712 rev 77) (Barbosa and Maldonado, 2015).

RESULTS

Red light photoperiod and PPFD did not influence hypocotyl length (HL) of purple cabbage microgreens. Also, there was no effect of the interaction between the factors (Table 1); HL were 6.95 and 7.18 cm for purple cabbage microgreens irradiated and not irradiated with red light, not differing from each other. Considering the factors and additional treatment, mean HL was 6.98 cm (Table 1).

Table 1. Summary of ANOVA and Tukey test for hypocotyl length (HL), cotyledon area (CA), yield and chlorophyll fluorescence of purple cabbage microgreens as a function of red light photoperiod (PP) and photosynthetic photon flux density (PPFD) and additional treatment (AT, white light). ** and ^{ns} correspond to significant ($p < 0.01$) and non-significant ($p > 0.05$) by *F* test, respectively. Means followed by the same letter in the column do not differ by Tukey test ($p > 0.05$). CV: Coefficient of variation.

	HL	CA	Yield	Chlorophyll
F values				
PP	1.66^{ns}	15.19^{**}	6.10^{**}	2.31^{ns}
PPFD	0.06^{ns}	8.24^{**}	0.55^{ns}	1.91^{ns}
PP × PPFD	0.26^{ns}	1.85^{ns}	1.06^{ns}	0.40^{ns}
AT × (PP × PPFD)	2.90^{ns}	35.23^{**}	64.66^{**}	0.00^{ns}
CV, %	3.57	5.97	3.60	3.57
	cm	cm^2 microgreen^{-1}	kg m^{-2}	Fluorescence
Photoperiod (h d^{-1})				
12	7.08^a	1.48^b	5.45^b	0.784^a
16	6.90^a	1.63^a	5.60^{ab}	0.801^a
20	6.86^a	1.74^a	5.78^a	0.771^a
PPFD (µmol m^{-2} s^{-1})				
20	6.93^a	1.56^b	5.58^a	0.793^a
40	6.96^a	1.67^a	5.64^a	0.777^a
Red light (factorial)	7.18^a	1.62^a	5.61^a	0.785^a
White light (control)	6.95^a	1.32^b	4.76^b	0.785^a

The cotyledon area (CA) of purple cabbage microgreens was influenced by photoperiod and PPFD, but there was no interaction between the factors (Table 1). Higher CAs were observed with photoperiods of 16 or 20 h d^{-1}, which promoted increments of 10.0% and 17.5% in CA compared to that obtained with 12 h d^{-1} red light. Microgreens irradiated with 40 µmol m^{-2} s^{-1} red light showed 7% higher CA than those cultivated with 20 µmol m^{-2} s^{-1}. Compared to microgreens that received only white light (control treatment), red light promoted 22.7% higher CA (1.62-1.32 cm^2 microgreen^{-1}) (Table 1).

Yield was influenced only by photoperiod, and no effects of PPFD and interaction between the factors were observed (Table 1). Higher yield was obtained with 20 h d^{-1} red light (5.78 kg m^{-2}). With 16 h d^{-1} light, yield corresponded to 97% of that obtained with 20 h d^{-1}, not differing from each other. Plants irradiated for 12 h d^{-1} with red light had the lowest yield, 5.45 kg m^{-2}, which corresponded to 94.4% of that obtained with 20 h d^{-1} red light. The yield of microgreens obtained with red light (5.61 kg m^{-2}) was 17.9% higher than that obtained in its absence (4.76 kg m^{-2}) (Table 1). Chlorophyll fluorescence was not influenced by the factors. There was also no difference for chlorophyll fluorescence of microgreens that received red light and those that did not, and the value observed was 0.785 in both conditions (Table 1).

DISCUSSION

In the plant factory environment, artificial lighting is the main management tool to enhance the photomorphogenetic, photosynthetic and metabolic processes of microgreens, improving crop growth and yield. Among the morphological characteristics, only cotyledon area (CA) was influenced by the factors photosynthetic photon flux density (PPFD) and photoperiod (Table 1). The CA stands out among the commercial

morphological characteristics of microgreens, since visually it is the part that draws the most attention from the consumer. It was observed that the addition of red to white light for 16 and 20 h d^{-1} promoted increases of 10.0% and 17.6% in CA compared to that obtained with 12 h d^{-1}, respectively. The positive result obtained with the increase in the red light photoperiod is explained by the prolongation of the photon absorption period, which favors CO_2 fixation and photosynthetic activity (Liu et al., 2022; Shibaeva et al., 2022), consequently promoting greater DM accumulation and greater growth. Additionally, red light has lower energy photons, which stimulated determine the expression of genes that strongly coordinate photomorphogenic and photosynthetic responses, generating changes in their morphology such as leaf expansion, among other processes (Paradiso and Proietti, 2022).

The relationship between the photoperiod and the quality of artificial lighting can lead to changes in plant morphology. Kong and Zheng (2020) found an increase in the CA of arugula, cabbage, kale, and mustard microgreens when red light was used, compared to blue, blue + green, and blue + UV lighting. Bantis (2021) found an increase in the CA of mustard and green basil microgreens under higher red light intensities. In our study, the addition of red LED to white LED corroborated the benefits of a higher proportion of red light observed in the reported studies. When supplementing white LED with 20 and 40 µmol m^{-2} s^{-1} with red LED, the irradiance of red light to the purple cabbage microgreens was increased by 24% and 48%, respectively, and consequently the relative proportions of red in relation to the blue, green and yellow wavelengths offered by the white LED were higher.

The positive effects of PPFD and photoperiod on CA led to yield increments (Table 1). Yield is a very important attribute for the microgreen producer, since this parameter conditions the greater or lesser optimization of the production structure, reducing or increasing the unit cost of the product. In the present study, adding red light (mean of the photoperiod-intensity factorial) to white light (additional treatment) promoted an increase of 17.9% (5.61 kg m^{-2}; 4.76 kg m^{-2}) in the yield of purple cabbage microgreens. Combinations of wavelengths with greater participation of red light promoted yield increments in more than 15 species of microgreens (Bantis, 2021; Frąszczak and Kula-Maximenko, 2022; Luo et al., 2024). Photosynthetic rates are relatively high when plants are illuminated under red wavelength (Hogewoning et al., 2010), which stimulates cell division, favoring plant growth, leaf expansion and, consequently, increased biomass. In the present study, the treatments with 20 and 40 µmol m^{-2} s^{-1} red light promoted increments of 24% and 48%, respectively, in the amount of this wavelength to the microgreens compared to what was provided by the white light. Under these conditions, the red:blue ratio is 1.38:1 and 1.59:1 compared to the 1.15:1 observed with white light.

The results observed for the biometry and yield of purple cabbage show that PPFD and photoperiod did not compromise the energy transfer from the antenna to the reaction centers of photosystem II (PSII). The chlorophyll fluorescence practically did not vary, with an average of 0.785 for the two light conditions (with and without red LED) (Table 1). No stress was observed on the photosystem, since values within the range of 0.75 to 0.80 are considered adequate (Krause et al., 2001). Thus, it can be understood that chlorophyll excitation energy was used for C fixation, biomass accumulation and yield increase. Medelo et al. (2025) also did not find significant difference (average of 0.76) for chlorophyll fluorescence of purple cabbage microgreens when evaluating harvest time (4 and 6 d light), photoperiod (12, 16 and 20 h d^{-1}) and white light irradiance (150 to 450 µmol m^{-2} s^{-1}).

CONCLUSIONS

Adding 20 µmol m^{-2} s^{-1} during 16 h d^{-1} of red light to white light (20 h d^{-1} and 250 µmol m^{-2} s^{-1}) allows obtaining higher cotyledon area and yield in purple cabbage microgreens.

Author contributions

Conceptualization: A.B.C.F., R.F.C., L.F.V.P. Methodology: A.B.C.F., R.F.C., L.F.V.P. Formal analysis: A.B.C.F. Investigation: M.J.Y.M., T.N.A., L.M.R., W.M.P., L.N.C.S. Data curation: M.J.Y.M., T.N.A., L.M.R., W.M.P., L.N.C.S. Writing-original draft preparation: M.J.Y.M., M.O.S. Writing-review and editing: A.B.C.F., R.F.C., L.F.V.P. Supervision: A.B.C.F. Project administration: A.B.C.F. All co-authors reviewed the final version and approved the manuscript before submission.

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