CHILEAN JOURNAL of AGRICULTURAL RESEARCH

CHILEANJAR
CHILEAN JOURNAL of AGRICULTURAL RESEARCH

RESEARCH ARTICLE

Harvest time, photoperiod and white light irradiance on yield of red cabbage microgreens in plant factory

Maria José Yañez Medelo[1], Thatiane Nepomuceno Alves[1], Laura Matos Ribera[2], Lucas Natan Camacho da Silva[1], Rogério Falleiros Carvalho[2], Alex Humberto Calori[3], and Arthur Bernardes Cecílio Filho[1*]

[1]Universidade Estadual Paulista (Unesp), Departamento Produção Vegetal, Jaboticabal, 14884-900, Brazil.
[2]Universidade Estadual Paulista (Unesp), Departamento de Biologia, Jaboticabal, 14884-900, Brazil.
[3]LEDs-up Soluções para cultivo, Mococa, 13737-015, Brazil.
[*]Corresponding author (arthur.cecilio@unesp.br).
Received: 18 July 2024; Accepted: 25 September 2024, doi:10.4067/S0718-58392025000200181

ABSTRACT

Plant factory is a production system characterized by high control and efficiency of the production factors, in which the cultivation of microgreens has increased. Photoperiod and photosynthetic photon flux density (PPFD) are two of the main factors to be investigated in order to obtain maximum yield. In this context, an experiment was conducted in indoor environment to evaluate the influence of photoperiod (12, 16 and 20 h d^{-1}) and PPFD (150, 250, 350 and 450 µmol m^{-2} s^{-1}) with two harvest times (4 and 6 d of light) on the growth and yield of red cabbage (*Brassica oleracea* L. var. *capitata* L.) microgreens. Early harvest, photoperiod and PPFD affected hypocotyl length (HL), cotyledon area (CA) and yield individually and in interaction. Two-day earlier harvest resulted in reductions of 10.0%, 32.0% and 16.5% in HL, CA and yield, respectively. In general, higher PPFD and photoperiod caused decrease in HL and increase in CA and yield. With the combination of these factors, 315 µmol m^{-2} s^{-1} with 20 h light promoted the highest yield of red cabbage microgreens. In one year of production, early harvest promotes a greater number of production cycles and higher yield of red cabbage microgreens (616 kg m^{-2}), which was 27% higher than that obtained with harvest carried out 2 d later, when the first leaf appeared.

Key words: *Brassica oleracea* var. *capitata*, functional food, indoor farm, light spectrum, photosynthetically active photon flux.

INTRODUCTION

The challenge of ending hunger is permanent. To this end, the UN (2022) proposes doubling crop yield, using resilient agricultural practices, with minimal disruption to ecosystems, and that are also strong in the face of climate change, such as drought, flood and other disasters. Historically, to increase food production, farmers have resorted mainly to the incorporation of potentially arable areas and increments in yield arising from new cultivars and heavy technological investment. However, unlike previous challenges, the challenge of meeting the 70% increase in food demand by 2050 (FAO, 2023) is greater, since: i) Agricultural frontiers are considerably reduced, with 90% centered in Latin America and Sub-Saharan Africa, of which 50% is located in only seven countries (FAO, 2023); ii) the pressure to maintain natural forests may contribute to lower incorporation of potentially arable areas into food production (Saath and Fachinello, 2018); iii) yield gains have not been as significant as in previous decades (Saath and Fachinello, 2018); iv) global warming has been compromising the yield of many species (Lima et al., 2022); and v) there has been increased pressure from society for agriculture with a lower environmental impact, both in the use of water and soil and in the use of more efficient inputs, with less generation of greenhouse gases (Pereira et al., 2021).

Plant factory is a production system that responds positively to the aforementioned issues. It is characterized by being highly technological, where the factors of production are precisely controlled promoting high yield and food quality. It also allows for the verticalization of production, which optimizes the area of land available for production (Wong et al., 2020). In this production system, considered as a new class of food, microgreens have been seen as a great option for growing and producing food in quantity and quality for the population, especially due to the high nutraceutical value and concentrations of bioactive compounds with beneficial actions in the prevention of diseases such as diabetes, obesity, cancer, and cardiovascular problems (Lanoue et al., 2022; Shibaeva et al., 2022). Among the most cultivated species, those in the Brassicaceae family stand out for showing not only rapid germination and short time for harvest, but mainly due to morphological and sensory attributes that are highly acceptable to consumers (Ramirez et al., 2020). Red cabbage is an interesting option due to its flavor, texture, color, high concentrations of vitamins C and E, carotenoids, lutein/zeaxanthin, which are important antioxidant factors (Yanes-Molina et al., 2019).

However, in this environment, given the absence of solar radiation, it is mandatory to establish irradiance protocols to obtain commercial-quality production. For being more efficient and effective in converting electricity into photons, the first LED luminaires for horticulture were combinations of blue and red (Kusuma et al., 2020) and today correspond to the vast majority of reports of studies for microgreens in indoor environment (Zhang et al., 2020). However, although less efficient, due to widespread use in lighting applications for human vision comfort, white LED are about 20% of the cost of red LED, which has contributed to increasing the fraction of white light to over 60% in some horticultural fixtures (Kusuma et al., 2020). In addition, due to the broad spectrum of radiation, white light can have actions that enhance physiological processes, which have repercussions on the growth and development of plants (Meng et al., 2019). Monochromatic green light is not efficient in converting electricity into photons, but it brings benefits when it is a component of white LED, as it has a greater capacity to penetrate the leaf profile than blue and red light, increasing photosynthesis by acting on lower chloroplasts (Nguyen et al., 2021). According to Yang et al. (2018), horticultural plants grown under white light showed higher photosynthetic activity than those under monochromatic light. Therefore, white LED can be a strategy to establish irradiance protocols for high yield and food quality, at a lower cost.

As for the photoperiod, it plays an important role in regulating the growth, development, and nutritional value of plants Liu et al. (2022). By keeping the flux of photosynthetic photons constant, greater biomass accumulation is expected with increasing photoperiod, since greater daily light energy is supplied to plants (Silva et al., 2022). When evaluating photoperiods (12 to 24 h) for lettuce in plant factory, Silva et al. (2022) found increments in leaf fresh and dry mass with up to 18 h light. For green cabbage, Liu et al. (2022) found higher biomass production with 20 h, while 14 h promoted better performance according to Filatov and Olonin (2023). No study on photoperiod for red cabbage microgreens was found.

For the success of agriculture in controlled environments, it is also necessary to adjust the photosynthetic photon flux density (PPFD) for the crop. No results were found for irradiance in red cabbage microgreens using white LED. According to Jones-Baumgardt et al. (2019), fresh mass (yield) is probably the most important metric of harvested production of microgreens, since they are sold by weight. These authors used LED with 15% blue and 85% red and a photoperiod of 16 h and, despite finding a 23% decrease in hypocotyl length for cabbage microgreens, they observed increments of 56% and 69% in the fresh and dry mass, respectively, as the PPFD increased from 100 to 600 μmol m^{-2} s^{-1}. Liu et al. (2022), with blue-red-green 1:1:1 LED, found that increasing irradiance from 30 to 90 μmol m^{-2} s^{-1} reduced the hypocotyl length of cabbage microgreens, while maximum values of fresh and dry mass were obtained with 90 and 70 μmol m^{-2} s^{-1}, respectively.

Studies on harvest time have not been found for red cabbage microgreens. As a standard for harvesting microgreens, the recommendation is that harvest should be performed upon the appearance of the first leaf (Shibaeva et al., 2022). However, this study hypothesizes that, although early harvesting reduces the hypocotyl length, leaf area and fresh and dry mass of the microgreens, it will not compromise sensory aspects of commercialization (visual presentation, mainly) and will allow the microgreen factory to obtain higher food production over the course of a year as it allows for more production cycles. In addition to this hypothesis, there is also the hypothesis that, even for the short period of lighting required to reach the harvest point, red cabbage will respond positively to the increase in photon flux and photoperiod. Thus, the objective of this study was to evaluate the effects of white light irradiance and photoperiod on the growth and yield of red cabbage microgreens.

MATERIAL AND METHODS

The experiment was conducted from 10 to 19 March 2023, at the Plant Factory Laboratory, with control of temperature for 20 ± 1 °C and relative humidity of 50% to 65%, at the Plant Production Department, São Paulo State University (UNESP), Jaboticabal campus, São Paulo, Brazil.

Treatments and experimental design

A total of 24 treatments were evaluated in split-split plots, with harvest time (4 and 6 d of light) in the plot, photoperiod (12, 16 and 20 h d^{-1}) in the sub-plot, and photosynthetic photon flux density (PPFD) (150, 250, 350 and 450 µmol m^{-2} s^{-1}) in the sub-subplot, with four replicates of the treatments. Each experimental unit corresponded to a shelf of the rack containing two trays of microgreens.

White LED lamps, 7 W, 48 VDC, model GLFS-v.11.7.4.22 (LEDs-up Soluções para cultivo, Mococa, São Paulo State, Brazil), composed of blue (25.4%), green (23.8%), yellow/orange (21.3%), red (27.1%) and far red (2.3%) were used (Figure 1). The lamps were distributed in order to obtain uniformity of the irradiances established in the treatments on the microgreen trays, checked by a spectroradiometer (SpectraPen SN-SP-144, Photon System Instruments, Brno, Czech Republic) placed on the same surface as the trays. The spectroradiometer sensor was placed next to the tray used to grow the microgreens with the sensor 5 cm above the surface, 27 cm away from the lamps.

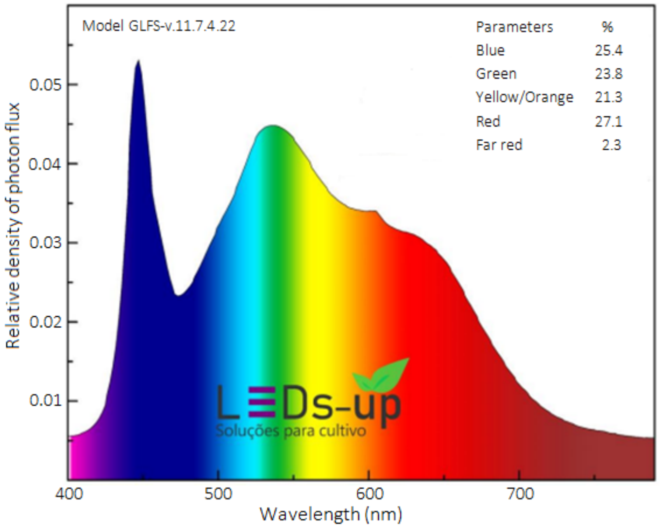

Figure 1. Relative density of photon flux and wavelength percentages of the white light (Leds-up Soluções para cultivo, Mococa, São Paulo State, Brazil).

Experimental conditions

The rectangular (14 × 11.5 × 4.5 cm) polypropylene trays were filled with a 1.5 cm thick layer of organomineral substrate for vegetables (Bioplant, Nova Ponte, Minas Gerais State, Brazil), which has pH 6 ± 0.3 and electrical conductivity of 0.8 dS m^{-1} ± 0.06. At the base of the trays, holes of 2 mm in diameter, equidistantly spaced 3 cm apart, were made to moisten the substrate with nutrient solution by capillarity.

Manual sowing was carried out by uniformly distributing 300 g m^{-2} seeds of red cabbage (*Brassica oleracea* L. var. *capitata* L.) 'Mamouth Red Rock' on the moist substrate, without incorporation. 'Mamouth

Red Rock' is recommended for autumn-winter planting, with an average cycle of 100 d (Feltrim Seeds, Farroupilha, Rio Grande do Sul State, Brazil). After sowing, the trays were sprayed with water to moisten the seed, stacked in lots of four trays and placed in a dark environment for germination, rooting of the seedlings in the substrate, and growth of the hypocotyl. Three days after sowing (DAS), two trays containing seedlings were placed in the center of larger trays and transferred to the laboratory for application of the treatments (light phase) (Figure 2). The trays were placed on vertical racks, with each treatment on a shelf, which had side protection to prevent light from spreading to other shelves.

Prior to the beginning of the irradiance of the treatments, 500 mL nutrient solution were applied to the larger tray to serve the two trays of microgreens (experimental unit, 322 cm^2). The criterion for replacing nutrient solution to the trays was the complete absorption of the nutrient solution provided. Then, on the first day, another 100 mL was applied to all treatments. For each experimental unit, in the treatments that received 12 or 16 h light, regardless of the light intensity, 300, 300, 300, 350 and 350 mL nutrient solution were applied, respectively. In the treatments under 20 h light, the volume of nutrient solution was the same as that reported for the other combinations of photoperiod and light intensity until the fourth day, with 100 mL more being applied per experimental unit on the fifth and sixth days. The nutrient concentrations of the nutrient solution proposed by Furlani et al. (1999) were 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} $N\text{-}NO_3^-$, $N\text{-}NH_4^+$, P, K, Ca, Mg, S, B, Cu, Fe, Mn, Mo and Zn, respectively.

Two harvests were carried out. The first was performed at 4 d of the light phase, when the seedlings only had fully expanded cotyledons, with no visualization of the first leaf. The second harvest was performed at 6 d of the light phase, when the microgreens showed the beginning of the growth of the first leaf.

Figure 2. Trays with microgreens recently removed from the dark phase and placed in a tray containing nutrient solution (A) and trays with microgreens ready for harvesting (B).

Variables

Cotyledon surface temperature: Using a camera FLIR, model C3-X (Teledyne FLIR, Wilsonville, Oregon, USA) with an infrared reading emitted by the surface of the red cabbage cotyledons, temperatures were recorded from the north, south, east, west and center of the tray and the average temperature was calculated.

Chlorophyll fluorescence: 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.

Yield: Microgreens from one tray were harvested by cutting the hypocotyl close to the substrate and immediately weighing them on a scale with 0.01 g precision. The estimated yield was expressed in g m^{-2}.

Hypocotyl length (cm): Fifty seedlings were randomly and carefully cut at the level of the substrate, which, prior to sowing, had its surface flattened and the seeds distributed over the substrate. After cutting, the seedlings were placed on the surface of the laboratory table and measured with a graduated ruler.

Cotyledon area (cm^2 per plant): Cotyledons from the 50 seedlings per experimental unit used to measure hypocotyl length were separated from the seedlings and passed through the LI 3100 electronic bench area meter (LI-COR, Tucson, Arizona, USA) to quantify cotyledon area.

Data analysis

The data for each characteristic was submitted to ANOVA (F test) according to the experimental design of split-split plots, with harvest time in the plot, photoperiod in the subplot and photosynthetic photon flux density (PPFD) in the sub-subplot, with four replicates of the treatments. Tukey test was applied to compare the means of the harvest time and photoperiod factors, and a polynomial regression study was performed for the PPFD factor, choosing the equation that was significant ($p < 0.05$) and with the highest coefficient of determination to better represent the distribution of the means.

RESULTS

The temperature of red cabbage cotyledons was influenced by the interaction between photoperiod and irradiance. The temperature difference in the cotyledons grown with the lowest and highest irradiance and photoperiod reached 6.8 °C (Table 1).

Table 1. Microgreen red cabbage cotyledon temperature as a function of photoperiod and irradiance. Means followed by the same lowercase letter in the row and uppercase letter in the column do not differ according to the Tukey test ($p > 0.05$).

	Cotyledons temperature (°C)			
	Irradiance (µmol m^{-2} s^{-1})			
Photoperiod (h)	150	250	350	450
12	21.6^{Bc}	23.2^{Bb}	26.9^{Aa}	27.6^{Aa}
16	21.8^{Bc}	24.9^{Ab}	27.5^{Aa}	28.3^{Aa}
20	24.7^{Ac}	24.6^{Ac}	27.2^{Ab}	28.4^{Aa}

Hypocotyl length (HL) was influenced by the individual factors and by the interactions between harvest time and PPFD and between photoperiod and PPFD. Harvesting with 6 d of light allowed 11.6% higher HL than with 4 d, and higher photoperiod (20 h) promoted HL similar to that obtained with 16 h photoperiod and about 3.5% lower than that obtained when seedlings were grown under 12 h (Table 2). According to the interaction between harvest time and irradiance, the 2 d delay in harvesting promoted higher HL, regardless of PPFD (Table 3). At both times, higher and lower HL values were obtained with 150 and 450 µmol m^{-2} s^{-1}, but there was a greater reduction in HL as irradiance increased with later harvest (10%) than with early harvest (5%) (Figure 3). Regarding the interaction between photoperiod and irradiance, HL responded differently to the photoperiod under each PPFD (Table 3), except for the 16 h photoperiod, under which, according to quadratic fit, HL increased from 150 to 255 µmol m^{-2} s^{-1} and decreased with higher PPFD up to 450 µmol m^{-2} s^{-1}; in seedlings under photoperiods of 12 and 20 h, HL decreased linearly within the irradiance interval studied. The similarity between the three photoperiods was that the lowest HL was obtained with the highest irradiance (Figure 4).

Table 2. Hypocotyl length (HL), cotyledon area (CA), yield, initial fluorescence (F_0), maximum fluorescence (F_m) and maximum photochemical efficiency (F_v/F_m) of microgreen red cabbage as a function of harvest time and photoperiod. Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$).

	HL	CA	Yield	F_0	F_m	F_v/F_m
Harvest time(d)	cm	cm^2 $plant^{-1}$	kg m^{-2}			
4	5.83^{b}	0.98^{b}	6.77^{b}	77.0^{a}	330.8^{a}	0.76^{a}
6	6.51^{a}	1.44^{a}	8.11^{a}	91.9^{a}	380.9^{a}	0.76^{a}
Photoperiod (h)						
12	6.27^{a}	1.12^{b}	6.91^{c}	85.65^{a}	353.63^{a}	0.76^{a}
16	6.19^{ab}	1.21^{ab}	7.42^{b}	86.40^{a}	361.60^{a}	0.76^{a}
20	6.06^{b}	1.30^{a}	7.99^{a}	81.19^{a}	349.28^{a}	0.76^{a}

Table 3 Hypocotyl length (cm) of microgreen red cabbage as a function of interactions between irradiance and harvest time and between irradiance and photoperiod. Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$).

	Irradiance (µmol m^{-2} s^{-1})			
Harvest time (d)	150	250	350	450
4	6.00^{b}	5.87^{b}	5.75^{b}	5.71^{b}
6	6.74^{a}	6.73^{a}	6.53^{a}	6.04^{a}
Photoperiod (h)				
12	6.55^{a}	6.29^{a}	6.17^{a}	6.04^{a}
16	6.23^{b}	6.42^{a}	6.18^{a}	5.95^{a}
20	6.34^{b}	6.18^{a}	6.07^{a}	5.65^{b}

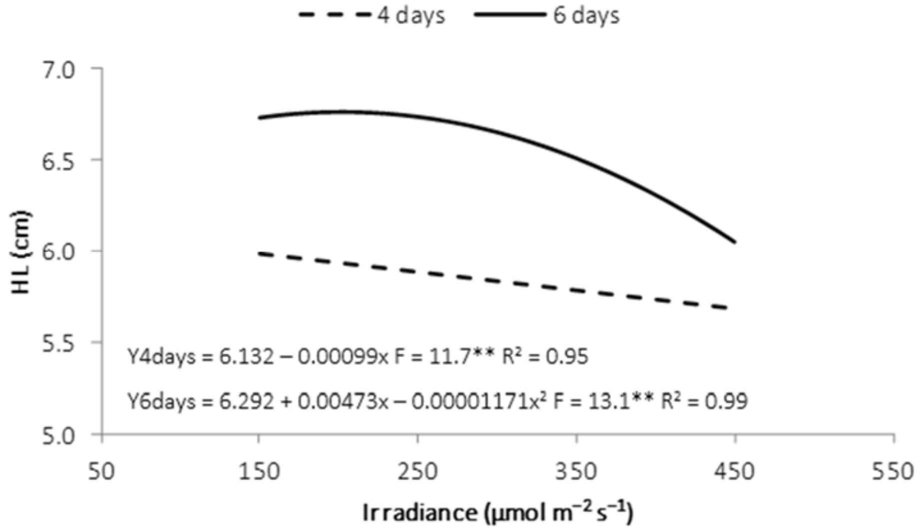

Figure 3. Hypocotyl length (HL) of red cabbage microgreen as a function of harvest time and irradiance.

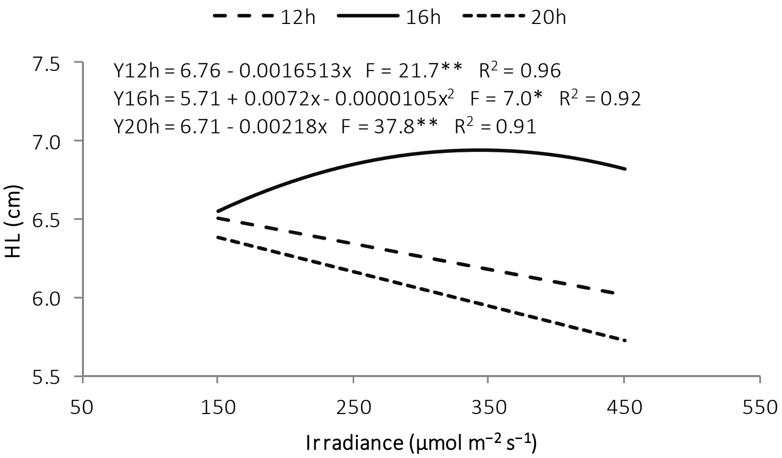

Figure 4. Hypocotyl length (HL) of red cabbage microgreen as a function of photoperiod and irradiance.

Cotyledon area was affected by the individual factors. Harvesting at 6 d of light promoted a 47% increase in cotyledon area compared to early harvest, and seedlings under 20 h of light showed a 16% larger cotyledon area than those cultivated under 12 h (Table 2). As a function of irradiance, the maximum cotyledon area was obtained at 390 µmol m^{-2} s^{-1} (Figure 5).

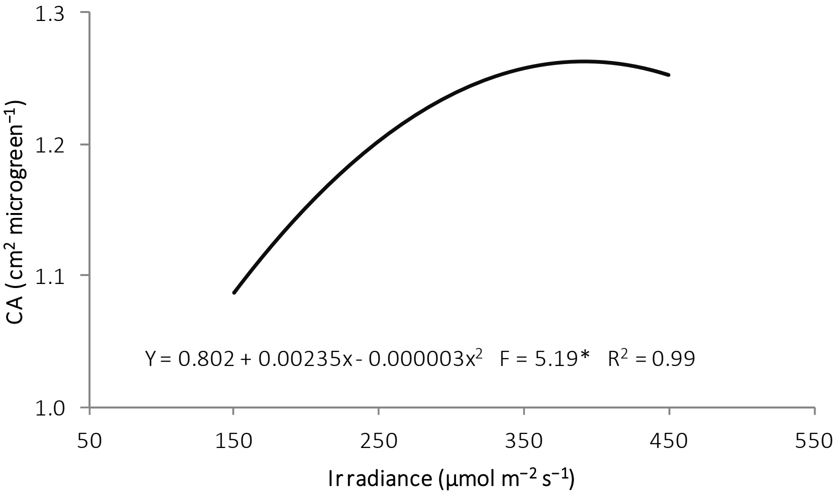

Figure 5. Cotyledon area (CA) of red cabbage microgreen as a function of irradiance.

Red cabbage yield was influenced by the individual factors (Table 2) and by the interaction between photoperiod and irradiance (Table 4, Figure 6). Under irradiances of 150, 250 and 350 µmol m^{-2} s^{-1}, the longer photoperiod promoted higher yields, with increments of 18%, 18% and 19% compared to the yields obtained with the same PPFD under 12 h. With 450 µmol m^{-2} s^{-1}, the yield obtained under 16 h did not differ from that observed under 20 h, and the mean obtained with these photoperiods was 9.8% higher than that for 12 h (Table 4). The highest yield (8.2 kg m^{-2}) was obtained under 20 h and 315 µmol m^{-2} s^{-1} and 25% higher than the lowest yield, which was obtained under 12 h and 150 µmol m^{-2} s^{-1} (Figure 6).

Table 4. Yield (kg m^{-2}) of microgreen red cabbage as a function of photoperiod and irradiance. Means followed by the same letter in the column do not differ by the Tukey test ($p > 0.05$).

Photoperiod (h)	Irradiance (µmol m^{-2} s^{-1})			
	150	250	350	450
12	6.58^{b}	6.84^{b}	6.94^{b}	7.28^{b}
16	6.76^{b}	7.34^{b}	7.49^{b}	8.09^{ab}
20	7.74^{a}	8.05^{a}	8.26^{a}	7.89^{a}

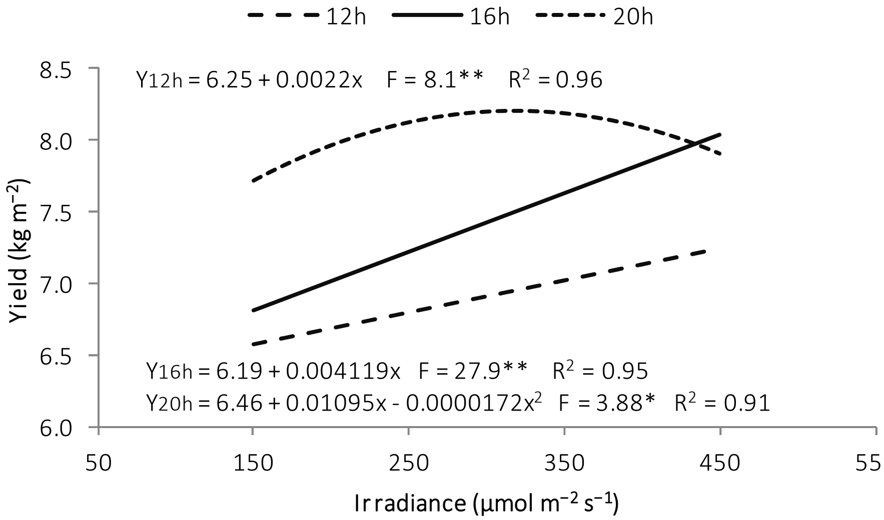

Figure 6. Yield of red cabbage microgreen as a function of photoperiod and irradiance.

DISCUSSION

Although the literature recommends harvesting the microgreens upon the appearance of the first leaf, early harvesting was carried out in order to assess whether the biometric characteristics and appearance would be commercially compromised. Appearance is one of the most important attributes of microgreens for their marketing. In the present study, no defects were observed due to artificial lighting (photoperiod and PPFD) and harvest time, such as oxidation by photoinhibition with the highest PPFD levels.

There are many studies on light in microgreens, especially those in the Brassicaceae family. The characteristics of this production factor modify the morphology, physiological processes and biochemical processes, which have repercussions on the growth, yield and quality of the microgreens. However, there are no standards set by the consumer as to the size of the hypocotyl and cotyledon area, which is good from a commercial point of view, since the consumer will not reject longer or shorter microgreens and larger or smaller cotyledons. However, one of the main morphological characteristics in microgreens is hypocotyl length (HL); a longer hypocotyl promotes better appearance and facilitates harvesting (Jones-Baumgardt et al., 2019). In the present study, seedlings harvested early had an average HL of 5.83 cm and were 10% smaller than seedlings harvested 2 d later (6.51 cm) (Table 2), being smaller with increasing irradiance and photoperiod (Figures 3 and 4).

Regarding the photoperiod, when analyzing the effect of the interaction between photoperiod and irradiance, a trend of depressive effect on HL was observed when the photoperiod was 20 h (Tables 2 and 3), which is consistent with Chen et al. (2021), who evaluated photoperiods (0 to 16 h) and red-blue light ratios for Chinese kale, and partially consistent with the results for cabbage reported by Liu et al. (2022), who observed an increase in HL up to 14 h of light per day, when evaluating photoperiods of 12 to 20 h under red-blue-green light in a 1:1:1 ratio. The divergence in the results is attributed to the lower irradiances (30 to 90 µmol m^{-2} s^{-1})

adopted by the authors, since high PPFD is known to result in lower hypocotyl growth. Notwithstanding, the greater HL for red cabbage, 4.7 to 6.0 cm, compared to those observed by Liu et al. (2022), 3.26 to 4.01 cm, may be due to the higher spectral composition of white light. When evaluating white LEDs, Toscano et al. (2021) were able to significantly increase stem length in *Amaranthus tricolor* L. and *Brassica rapa* L. subsp. *oleifera* microgreens, since the presence of green light can counteract the depressive effect of blue light on hypocotyl growth (Folta, 2004; Park et al., 2010).

The effect of increasing PPFD reducing the HL of red cabbage is in agreement with results described in the literature, such as those observed for kohlrabi, mizuna and mustard microgreens (Gerovac et al., 2016), cabbage, arugula, kale and mustard greens (Jones-Baumgardt et al., 2019), broccoli (Gao et al., 2021), and cabbage and Chinese kale microgreens (Liu et al., 2022). Low PPFD favors hypocotyl etiolation (Niroula et al., 2021), which may be related to reduced concentration of gibberellins with higher PPFD levels (Potter et al., 1999), as these are hormones responsible for hypocotyl elongation (Binenbaum et al., 2018).

Regardless of harvest time, irradiance and photoperiod, HL values were suitable for marketing and mechanical harvesting, for which hypocotyls with minimum length of 5 cm are preferred according to Toscano et al. (2021).

The cotyledon area of red cabbage increased as the light time increased, either due to harvest delay (4 and 6 d of light) or due to a longer photoperiod (12, 16 and 20 h) (Table 2), in agreement with Hwang et al. (2022). A similar effect was observed with irradiance, as the cotyledon area increased 16% from 150 (1.087 cm^2 seedling^{-1}) to 390 µmol m^{-2} s^{-1} (1.262 cm^2 seedling^{-1}), remaining stable (variation of less than 1%) up to the irradiance of 450 µmol m^{-2} s^{-1}. Jones-Baumgardt et al. (2020) found a larger cotyledon area of cabbage with 300 µmol m^{-2} s^{-1}. The increase in cotyledon area observed for red cabbage agreed with results observed by Chen et al. (2021), Orlando et al. (2022) and Hwang et al. (2022).

Fresh mass is considered by Jones-Baumgardt et al. (2019) to be the most important harvest metric for the marketing of microgreens because they are usually sold by fresh weight. The yield observed in the study was influenced by the interaction between photoperiod and irradiance. Under irradiances from 150 to 350 µmol m^{-2} s^{-1}, the longer the photoperiod, the higher the yield. The yield of red cabbage under 20 h did not differ from that obtained with 16 h, but was higher than that obtained under 12 h (Table 4). Liu et al. (2022) also obtained higher cabbage yield with 20 h of light per day, when evaluating intervals of 12 to 20 h. In cabbage hydroponically cultivated for 3 wk, Lefsrud et al. (2006) observed an increase in fresh mass (yield) with the increase in photoperiod from 6 to 24 h, and numerous studies cited by Lefsrud et al. (2006) correlate the increase in yield in response to increasing photoperiod to the increase in leaf concentration of chlorophylls.

The increase in PPFD was decisive for increasing yield, regardless of the photoperiod adopted. The highest yield of red cabbage (8.2 kg m^{-2}) was obtained under 20 h and 315 µmol m^{-2} s^{-1}, surpassing by 9.5% the yield obtained under 16 h and 315 µmol m^{-2} s^{-1} and by 25% the lowest yield, which was obtained under 12 h and 150 µmol m^{-2} s^{-1} (Figure 6). Significant savings in electrical energy can be achieved if the 5% loss in the maximum yield is considered, which would require 165 µmol m^{-2} s^{-1}, almost 50% less than that required to obtain maximum yield, maintaining the photoperiod of 20 h. Also, the PPFD that promoted maximum yield of red cabbage was lower than the range of 400 to 500 µmol m^{-2} s^{-1}observed for cabbage by Jones-Baumgardt et al. (2019). Another difference is that the yield reduction observed in red cabbage from 315 µmol m^{-2} s^{-1} was only observed by Jones-Baumgardt et al. (2019) from 500 µmol m^{-2} s^{-1}. However, these authors worked with blue-red light and shorter photoperiod (16 h). Although higher PPFD and photoperiod contribute to lower HL, they are also known to contribute positively to photosynthetic rate, transpiration, stomatal conductance (Yang et al., 2014; 2018), and overall robustness of microgreens (Jones-Baumgardt et al., 2019; Chen et al., 2021). On the other hand, lower irradiances negatively affect the C balance, reducing net photosynthesis, characteristics that lead to lower growth of microgreens.

Regarding harvest time, yield was 16.5% lower when harvest was carried out early. On the other hand, early harvesting allows for a greater number of production cycles per year, 91 cycles with 4 d of light *vs.* 60 cycles with 6 d of light. For this reason, and according to the yields obtained (Table 2), the yields of red cabbage microgreens with harvests carried out with 4 and 6 d of light and similar energy expenditure for 1 yr production (7280 and 7200 h for cycles of 4 and 6 d, respectively) reach 616 and 486 kg m^{-2} yr^{-1}, respectively, hence 26.7% higher.

Appearance is one of the most important attributes of micro vegetables for marketing. In this study, no defects caused by photo-oxidation were observed at the higher PPFD and photoperiod. Also, the higher temperatures did not cause visual and physiological damage to the microgreens with increases in temperature and photoperiod, since higher yields were achieved under 20 h of light and 315 µmol m^{-2} s^{-1}. The nonsignificant results of initial fluorescence (F_0), maximum fluorescence (F_m) and maximum photochemical efficiency (F_v/F_m) indicate that the cultivation season, photoperiod and irradiance were not able to compromise the energy transfer from the antenna to the reaction centers of photosystem II. The F_v/F_m ratios practically did not vary, with average of 0.76 for the two harvest times, for the photoperiods and PPFD levels evaluated. According to Ahammed et al. (2018), the F_v/F_m ratio can be an indirect indicator of stress that shows stress-induced changes in photosynthesis. However, 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.

CONCLUSIONS

The study showed that white light and irradiance/photoperiod ratio influence the biometric characteristics of red cabbage microgreens. Higher irradiances and photoperiod with white light reduce hypocotyl length, but have the opposite effect on the cotyledon area and yield of red cabbage microgreens, which is maximized with 315 µmol m^{-2} s^{-1} and 20 h of light. Lower values of hypocotyl length, cotyledon area and yield were observed with early harvest. However, the 2 d shorter production cycle promotes a greater number of production cycles, with 616 kg m^{-2} of red cabbage microgreens produced in the period of 1 yr, whose yield is 27% higher than that obtained with harvest carried out 2 d later, when the first leaf appeared.

Author contributions

All authors contributed to the study conception and design. Conceptualization: A.B.C.F., R.F.C. Methodology: A.B.C.F., R.F.C. Investigation: M.J.Y.M., T.N.A., L.M.R., L.N.C.S., A.H.C. Data curation: M.J.Y.M., T.N.A., L.M.R., L.N.C.S., A.H.C. Formal analysis: A.B.C.F. Writing-original draft: M.J.Y.M., T.N.A., R.F.C. Resources: A.B.C.F. Supervision: A.B.C.F. Project administration: A.B.C.F. Writing-review & editing: A.B.C.F., R.F.C. All authors read and approved the final manuscript.

Acknowledgements

To Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq) and Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES).

References

Ahammed, G.J., Xu, W., Liu, A., Chen, S. 2018. *COMT1* silencing aggravates heat stress-induced reduction in photosynthesis by decreasing chlorophyll content, photosystem II activity, and electron transport efficiency in tomato. Frontiers in Plant Science 9:998. doi:10.3389/fpls.2018.00998.

Binenbaum, J., Weinstain, R., Shani, E. 2018. Gibberellin localization and transport in plants. Trends in Plant Science 23:410-421. doi:10.1016/j.tplants.2018.02.005.

Chen, J., Chen, Z., Li, Z., Zhao, Y., Chen, X., Wang-Pruski, G., et al. 2021. Effect of photoperiod on Chinese kale (*Brassica alboglabra*) sprouts under white or combined red and blue light. Frontiers in Plant Science 11:589746. doi:10.3389/fpls.2020.589746.

FAO. 2023. Crops and livestock products. FAO, Rome, Italy. Available at https://www.fao.org/faostat/en/#data/QCL (accessed 20 June 2023).

Filatov, D., Olonin, I. 2023. Optimal ratio of spectrum, light intensity and photoperiod to minimize costs when growing microgreens. E3S Web of Conferences 383:04074. doi:10.1051/e3sconf/202338304074.

Folta, K.M. 2004. Green light stimulates early stem elongation, antagonizing light-mediated growth inhibition. Plant Physiology 135:1407-1416. doi:10.1104/pp.104.038893.

Furlani, P.R., Silveira, L.C.P., Bolonhesi, D., Faquin, V. 1999. Cultivo hidropônico de plantas. Boletim Tecnico 180. Instituto Agronômico IAC, Campinas, São Paulo, Brasil.

Gao, M., He, R., Shi, R., Zhang, Y., Song, S., Su, W., et al. 2021. Differential effects of low light intensity on broccoli microgreens growth and phytochemicals. Agronomy 11:537. doi:10.3390/agronomy11030537.

Gerovac, J.R., Craver, J.K., Boldt, J.K., Lopez, R.G. 2016. Light intensity and quality from sole-source light-emitting diodes impact growth, morphology, and nutrient content of brassica microgreens. HortScience 51:497-503. doi:10.21273/HORTSCI.51.5.497.

Hwang, H.S., Jeong, H.W., Jeong, J.H., Jo, D.H., Hwang, S.J. 2022. Changes in growth and anthocyanin content of *Brassica juncea* L. affected by light intensity and photoperiod in plant factory with artificial lighting. Korean Journal of the Horticultural Science and Technology 40:586-594. doi:10.7235/HORT.20220053.

Jones-Baumgardt, C., Llewellyn, D., Ying, Q., Zheng, Y. 2019. Intensity of sole-source light-emitting diodes affects growth, yield, and quality of Brassicaceae microgreens. HortScience 54:1168-1174. doi:10.21273/HORTSCI13788-18.

Jones-Baumgardt, C., Ying, Q., Zheng, Y., Bozzo, G.G. 2020. The growth and morphology of microgreens is associated with modified ascorbate and anthocyanin profiles in response to the intensity of sole-source light-emitting diodes. Canadian Journal of Plant Science 101:212-228. doi:10.1139/cjps-2020-0060.

Krause, G.H., Koroleva, O.Y., Dalling, J.W., Winter, K. 2001. Acclimation of tropical tree seedlings to excessive light in simulated tree-fall gaps. Plant, Cell & Environment 24:1345-1352. doi:10.1046/j.0016-8025.2001.00786.x.

Kusuma, P., Pattison, P.M., Bugbee, B. 2020. From physics to fixtures to food: Current and potential LED efficacy. Horticultural Research 7:56. doi:10.1038/s41438-020-0283-7.

Lanoue, J., Louis, S., Little, C., Hao, X. 2022. Continuous lighting can improve yield and reduce energy costs while increasing or maintaining nutritional contents of microgreens. Frontiers in Plant Science 13:983222. doi:10.3389/fpls.2022.983222.

Lefsrud, M.G., Kopsell, D.A., Augé, R.M., Both, A.J. 2006. Biomass production and pigment accumulation in kale grown under increasing photoperiods. HortScience 41:603-606. doi:10.21273/HORTSCI.41.3.603.

Lima, R.F., Oliveira, A.L.E., Torsoni, G.B., Chiquitto, A.G., Moraes, J.R., Rolim, S.G. 2022. Agroclimatic zoning for the incidence of brown eye spot on coffee under climate change scenarios. Theoretical and Applied Climatology 149:1471-1496. doi:10.1007/s00704-022-04123-3.

Liu, K., Gao, M., Jiang, H., Ou, S., Li, X., He, R., et al. 2022. Light intensity and photoperiod affect growth and nutritional quality of brassica microgreens. Molecules 27:883. doi:10.3390/moléculas27030883.

Meng, Q., Kelly, N., Runkle, E.S. 2019. Substituting green or far-red radiation for blue radiation induces shade avoidance and promotes growth in lettuce and kale. Environmental Experimental Botany 162:383-391. doi:10.1016/j.envexpbot.2019.03.016.

Nguyen, T.K.L., Cho, K.M., Lee, H.Y., Cho, D.Y., Lee, G.O., Jang, S.N., et al. 2021. Effects of white LED lighting with specific shorter blue and/or green wavelength on the growth and quality of two lettuce cultivars in a vertical farming system. Agronomy 11:2111. doi:10.3390/agronomy11112111.

Niroula, A., Amgain, N., Rashmi, K.C., Adhikari, S., Acharya, J. 2021. Pigments, ascorbic acid, total polyphenols and antioxidant capacities in deetiolated barley (*Hordeum vulgare*) and wheat (*Triticum aestivum*) microgreens. Food Chemistry 354:129491. doi:10.1016/j.foodchem.2021.129491.

Orlando, M., Trivellini, A., Incrocci, L., Ferrante, A., Mensuali, A. 2022. The inclusion of green light in a red and blue light background impact the growth and functional quality of vegetable and flower microgreen species. Horticulturae 8:217. doi:10.3390/horticulturae8030217.

Park, J.W., Kang, P., Park, H., Oh, H.Y., Yang, J.H., Kim, Y.H., et al. 2010. Synthesis and properties of blue-light-emitting anthracene derivative with diphenylamino-fluorene. Dyes and Pigments 85:93-98. doi:10.1016/j.dyepig.2009.10.009.

Pereira, B.J., Cecílio Filho, A.B., La Scala Junior, N. 2021. Greenhouse gas emissions and carbon footprint of cucumber, tomato and lettuce production using two cropping systems. Journal of Cleaner Production 282:124517. doi:10.1016/j.jclepro.2020.124517.

Potter, T.I., Rood, S.B., Zanewich, K.P. 1999. Light intensity, gibberellin content and the resolution of shoot growth in *Brassica*. Planta 207:505-511. doi:10.1007/s004250050510.

Ramirez, D., Victorio-Abellán, A., Beretta, V., Camargo, A., Moreno, D.A. 2020. Functional ingredients from Brassicaceae species: Overview and perspectives. International Journal of Molecular Sciences 21:1998. doi:10.3390/ijms21061998.

Saath, K.C.O., Fachinello, A.L. 2018. Crescimento da demanda mundial de alimentos e restrições do fator terra no Brasil. Revista de Economia e Sociologia Rural 56:195-212. doi:10.1590/1234-56781806-94790560201.

Shibaeva, T.G., Sherudilo, E.G., Rubaeva, A.A., Titov, A.F. 2022. Continuous LED lighting enhances yield and nutritional value of four genotypes of Brassicaceae microgreens. Plants 11:176. doi:10.3390/plants11020176.

Silva, L.M., Cruz, L.P., Pacheco, V.S., Machado, E.C., Purquerio, L.F.V., Ribeiro, R.V. 2022. Energetic efficiency of biomass production is affected by photoperiod in indoor lettuce cultivation. Theorical and Experimental Plant Physiology 34:265-276. doi:10.1007/s40626-022-00246-0.

Toscano, S., Cavallaro, V., Ferrante, A., Romano, D., Patané, C. 2021. Effects of different light spectra on final biomass production and nutritional quality of two microgreens. Plants 10:1584. doi:10.3390/plants10081584.

UN. 2022. End hunger, achieve food security and improved nutrition and promote sustainable agriculture. United Nations (UN), Department of Economic and Social Affairs, New York, USA. Available at https://sustainabledevelopment.un.org/sdg2 (accessed on 15 May 2023)

Wong, C.E., Teo, Z.W.N., Shen, L., Yu, H. 2020. Seeing the lights for leafy greens in indoor vertical farming. Trends in Food Science & Technology 106:48-63. doi:10.1016/j.tifs.2020.09.031.

Yanes-Molina, A.P., Jaime-Meuly, R., Andrade-Bustamante, G., Lucero-Flores, T.I., Martinez-Ruiz, F.E. 2019. Microgreens-an alternative of horticultural production and market. Expert Journal of Marketing 7:120-136. http://hdl.handle.net/11159/4595

Yang, F., Huang, S., Gao, R., Liu, W., Yong, T., Wang, X., et al. 2014. Growth of soybean seedlings in relay strip intercropping systems in relation to light quantity and red:far-red ratio. Field Crop Research 155:245-253. doi:10.1016/j.fcr.2013.08.011.

Yang, X., Xu, H., Shao, L., Li, T., Wang, Y., Wang, R. 2018. Response of photosynthetic capacity of tomato leaves to different LED light wavelength. Environmental and Experimental Botany 150:161-171. doi:10.1016/j.envexpbot.2018.03.013.

Zhang, X., Bian, Z., Yuan, X., Chen, X., Lu, C. 2020. A review on the effects of light-emitting diode (LED) light on the nutrients of sprouts and microgreens. Trends in Food Science and Technology 99:203-216. doi:10.1016/j.tifs.2020.02.031.