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Article

Effect of supplementary pulsed LED light on lettuce growth under a greenhouse

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Abstract

The intermittent LED light with short on/off pulses as a source of supplementary light to sunlight could promote greater vegetable growth with a consequent lower energy consumption; nevertheless, its effect on lettuce (*Lactuca sativa* L.) under greenhouse conditions has been little studied. The work evaluated how different regimes of pulsed LED light affect the photosynthetic rate, stomatal conductance, leaf area, and fresh and dry weight, considered plant growth parameters. These parameters were analyzed under a completely randomized experimental design, establishing five treatments, with a total of 8 plants grown per treatment, applying LED light on them as a source of supplementary light to sunlight at night. The results indicated that the pulsed LED light with short on/off periods (30/15 min) does not produce significant differences (Anova, $p > 0.05$) in photosynthetic rates, stomatal conductance, and fresh or dry weight between the supplementary pulsed and continuous LED light. The pulsed light (30/15 min) produces a statistically significant increase (Anova, $p = 7.15 \times 10^{-5}$) in terms of leaf area compared to the continuous LED light, allowing a 25% reduction in the operating time of the lighting system without negatively affecting this parameter.

Keywords:

Lactuca sativa L., energy saving, greenhouse, photoperiod, photosynthesis.

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Introduction

Light is the primary source of energy that activates photosynthesis, responsible for transforming light energy into chemical energy from carbohydrates in plants (He *et al*., 2019). The intensity and quality of light incident on plants significantly affect the rate of photosynthesis; the photosynthetic photon flux density PPFD ((mol m^{-2} s^{-1}) refers to the intensity of light available for photosynthesis, significantly affecting the rate at which plants can produce carbohydrates that they will use for their growth (Jishi *et al*., 2016; Burattini *et al*., 2017).

The use of LED lights in controlled environment agriculture has increased considerably; in greenhouses, these devices are used as a source of supplementary light to the sun (He *et al*., 2019). A key advantage of LED light in agriculture is its lower energy consumption. In addition, the red (600-650 nm) and blue (450-470 nm) spectra regulate the stomatal opening and chlorophyll synthesis, directly affecting the photosynthetic rate, and have a high luminous efficiency so that the proportion of light energy emitted at a specific wavelength is more beneficial for the plant than other conventional light sources (Chen *et al*., 2017; Ali *et al*., 2023).

There are no studies that quantify the effects of 30 min/15 min (on/off) intermittency as a complementary light source on leaf area, plant height, and photosynthetic parameters in *Lactuca sativa* under greenhouse conditions. The existing results show contrasts, which derive mainly from the different configurations that vary the intermittency time, photoperiod, quality, and spectral proportions, together with the intrinsic response of each plant species (Chen *et al*., 2017; Radetsky *et al*., 2020; Boros *et al*., 2023).

By managing light/dark cycles, it has been possible to increase the biomass in crops such as basil, in addition to enhancing photosynthetic activity; however, on the other hand, periods of very short intermittency may not provide enough energy for plants to fully carry out their photosynthetic process (Chinchilla *et al*., 2018; Viršil# *et al*., 2020; Avgoustaki *et al*., 2021a; Yang *et al*., 2022).

The crop of lettuce (*Lactuca sativa* L.), with a compact architecture, is ideal for measuring its height, leaf geometry, and leaf area under light regimes. In addition, it adapts very well to intensive production systems due to its small size (Ali *et al*., 2023). There is no information on the use of pulsed light supplied supplementarily in night periods for short intermittency periods in lettuce; due to the above, the present research proposes to verify if using pulsed LED light, combined with RGB spectra, promotes positive effects on growth and photosynthetic parameters comparable to those of continuous light in terms.

The research aimed to provide evidence on how lettuce crops respond to light supplementation over various short periods, quantified in terms of photosynthetic rate, and how this affects plant development, which will enable a better understanding of the relationship between light intermittency and the response of plants to optimize their growth. It also sought to validate whether short light intermittency will not significantly reduce photosynthetic rate or leaf growth compared to continuous LED light supplied at night under greenhouse conditions.

Materials and methods

Description of the experimental site and treatments

The experiment is established in a multi-tunnel greenhouse with a polyethylene roof equipped with a wet-wall refrigeration system, located at coordinates 25.460833° north latitude and 100.970227° west longitude at an elevation of 1 500 masl. Five treatments (T1 to T5) were formed with crops of lettuce of the Paris Island variety. Treatment T1 consisted of the cultivation of lettuce under conditions of sunlight alone; in treatments T2 to T5, it was sought to extend the photoperiod by complementing the natural light with LED light provided only at night (Figure 1a).

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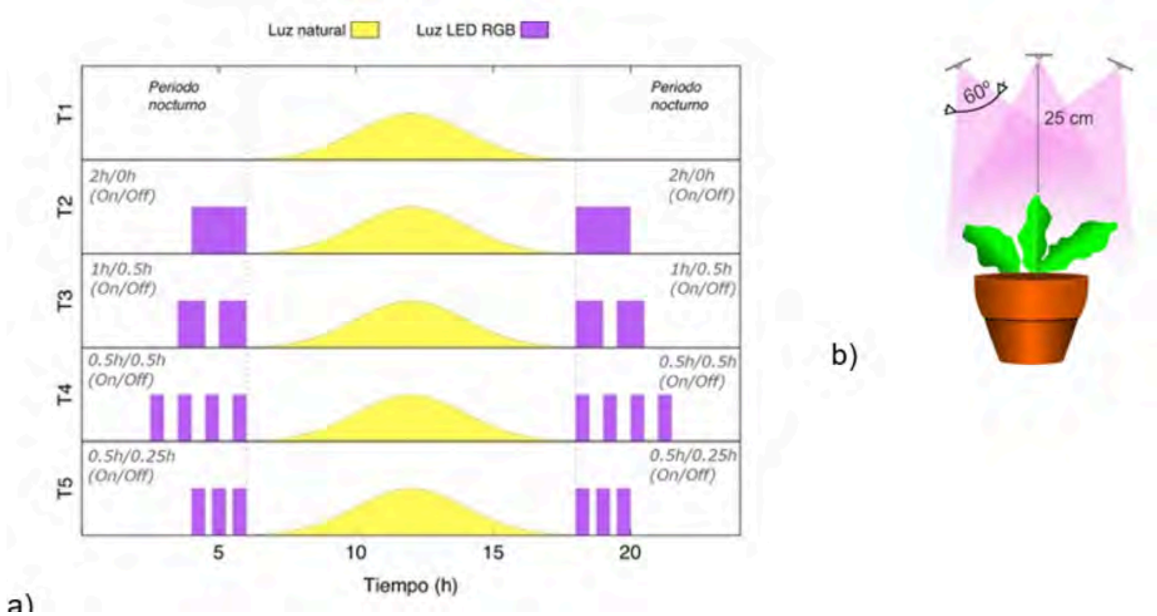
Figure 1. a) Treatment T1, with natural light, and treatments T2 to T5, with complementary LED light with different lengths and start time of the on-off periods; b) Front representation of the arrangement of LED lights positioned in a row parallel to the lines of the lettuce plants to maintain an intensity of 200 µmol m^{-2} s^{-1}.



The total daily LED light operating time in treatments T2 to T4 was 4 h, applying 2 h before dawn and 2 h after dusk. In the case of T5, the daily operating time was 3 h, applying 1.5 h before dawn and after dusk, respectively. The on/off ratio was the main factor, with levels of 2 h/0 h (T2), 2 h/1 h (T3), 0.5 h/0.5 h (T4), and 0.5 h/0.25 h (T5). These periods of artificial light complemented the period of natural light for a photoperiod of 16 h for T2 to T4, except for T5, which had a photoperiod of 15 h. Each treatment consisted of eight pots arranged in a straight line, with each pot containing a lettuce plant.

Photosynthetic rate and stomatal conductance readings were recorded at 29 days after transplantation, measured in the apex portion, taking three readings on young adult leaves located in the intermediate whorl of each plant at noon; five randomly selected plants were considered for each of the five treatments (T1-T5), and each reading was analyzed as an independent biological replication.

Lighting system with LED lights

The lighting lamps were made up of red-green-blue (RGB) LED lights, model LED-P1RGBLLLL-120/43-N, emitting light in the wavelengths of 600-650 nm, 520-530 nm, and 450-470 nm for the red (R), green (G), and blue (B) channels, respectively. All the lights were arranged in simple strips, with three strips for each row of plants (Figure 1b). Each LED bulb has a power of 3W, with transparent encapsulation.

The LED lights were also equipped with 13 mm acrylic convex lenses to obtain an opening angle of 60° and thus concentrate more light towards the plants. All LED lamps were calibrated to obtain a PPFD of 200 µmol m^{-2} s^{-1} ± 15 µmol m^{-2} s^{-1} measured at 25 cm from the center of the pots using a quantum sensor (LI-193SA, LI-COR), establishing a spectra ratio of 16R:1G:3B for all RGB LED light treatments as a generalization of related work (van Deldel *et al*., 2021). The LED lamps were always adjusted according to the growth in height of the plants to maintain the distance of 25 cm between lamps and plants (Figure 1b).

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Establishment of the crop

Twenty-one days after sowing, the seedlings were transplanted into 5 L pots with perlite as substrate. All treatments were fertilized with Steiner's universal solution, maintaining a drainage of the nutrient solution of 15-20%, which was applied by an automated irrigation system. In addition, micronutrients were applied equally in all treatments.

At 30 days after transplanting, plant growth parameters were recorded, among which are plant height, leaf length and width (measured in the central part of the longitudinal axis of the leaf), photosynthesis rate and stomatal conductance with a LI-COR LI-6400XT equipment, selecting five plants at random, with three measurements per plant, which were considered as independent observations within each treatment.

To estimate the leaf area, high-resolution images of the unfolded leaves of each plant were collected, which were taken captured from five plants with the RGB camera of a mobile device; subsequently, the fresh weight of the foliage was recorded by an analytical balance, and the dry weight was determined from samples placed inside a drying oven (OV-490A-2, Blue M Electric Company) at 70°C for 48 h.

Calculation of the daily light integral (DLI)

Inside the greenhouse, the global solar radiation was measured using two pyranometer sensors (LI-200R, LI-COR); the average daily readings were converted to PPFD units according to (Reis and Ribeiro, 2020); Equation 1 was used to calculate the daily light integral (DLI), and thus the amount of natural and artificial light that the plants received was quantified. The DLI was calculated using the following equation (He *et al*., 2019):

$$\mathrm{DLI}\left(\frac{\mathrm{mol}}{\mathrm{m^2 day}}\right)=\frac{\left(\mathrm{PPFD}\left(\frac{\mu\mathrm{mol}}{\mathrm{m2s}}\right)\times \mathrm{photoperiod}\left(\frac{\mathrm{h}}{\mathrm{day}}\right)\times 3600\left(\frac{\mathrm{s}}{\mathrm{h}}\right)\right)}{10^6} \quad 1).$$

Statistical analysis

The data obtained are analyzed employing a completely randomized experimental design using the R v4.2.3 software (R Core Team, 2023). Previously, the data are subjected to the verification of the assumptions of normality and homoscedasticity through Shapiro-Wilk and Bartlett tests, respectively, carrying out an analysis of variance (Anova) based on a level of significance $\alpha= 0.05$, and using a Tukey test ($p\leq 0.05$) to verify differences between the treatments and evaluating the size of the effect (η^2) for each parameter studied (Sullivan and Feinn, 2012).

Results and discussion

The lettuce crop cycle was inspected weekly; the average temperature to which the plants were subjected was 23.2 °C, with an average value of 18.4 °C and 29.7 °C for minimum and maximum temperatures, respectively, from July to September 2024. The average daily light integral (DLI) corresponding to the PAR radiation (400-700 nm) received by all treatments due to the effect of natural light inside the greenhouse was 8.75 mol m^{-2} day^{-1} and standard deviation (SD) of 0.912 mol m^{-2} day^{-1}, with its corresponding daily variations generated by the outdoor climatic conditions.

The DLI values corresponding to the LED light complementary to sunlight per day were 2.16 and 2.88 mol m^{-2} day^{-1} for lengths of 3 h and 4 h supplied to T5 and T2-T4, respectively (Table 1), applied without variations in terms of intensity, spectrum proportion, and operating schedule specific to each treatment (Figure 1a).

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Table 1. Average daily light integral (DLI) supplied to each of the treatments during the crop cycle from transplanting.

Treatment	DLI (mol m^{-2} day^{-1})	Condition
T1	8.75	Natural light
T2	11.63	Natural light + continuous LED Light
T3	11.63	Natural light + pulsed LED light
T4	11.63	Natural light + pulsed LED light
T5	10.91	Natural light + pulsed LED light

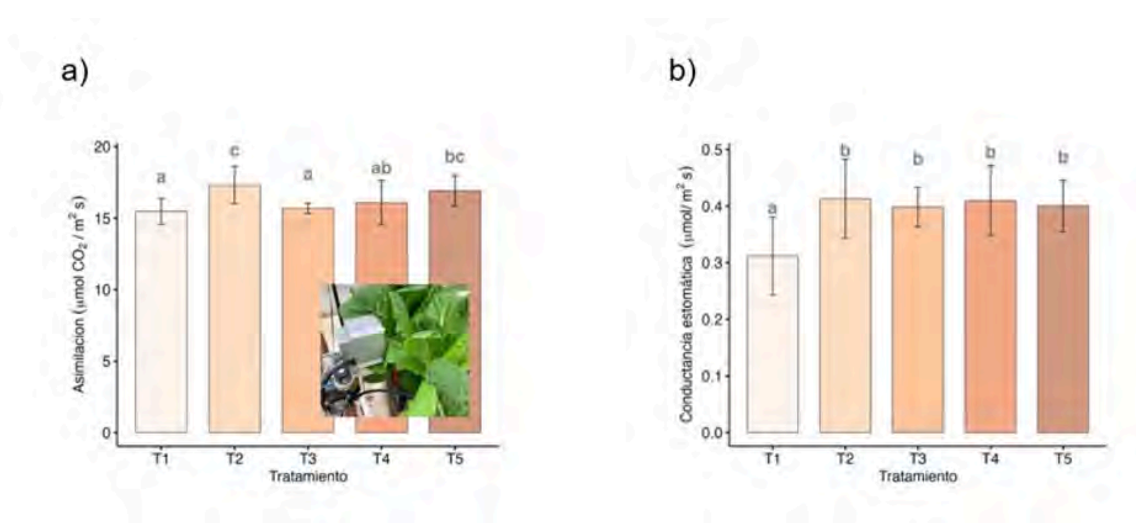
In their study, Boros *et al*. (2023) state that the optimal condition range of PPFD for lettuce plants is 200-250 µmol m^{-2} s^{-1} with a photoperiod of 16 h to result in a DLI of between 11.52 to 14.4 mol m^{-2} day^{-1}, which involves only the PAR radiation spectrum; this statement is valid for an R/B ratio of 2.2. Under this criterion, the DLI supplied to T1 would be insufficient; this effect is attributed to the level of transmissivity of the greenhouse cover; on the other hand, treatments T2 to T5 would be within the recommended PPFD range.

For their part, He *et al*. (2019) report that a DLI of 14.4 mol m^{-2} day^{-1} at a PPFD of 250 µmol m^{-2} s^{-1} is sufficient; under this criterion, the treatments established in the present study are slightly below, although it should be considered that the combination of factors, such as light quality, intensity, photoperiod, climatic factors, plant species, and cultivated variety, significantly influence plant growth and development (Dutta Gupta, 2017; Boros *et al*., 2023). Given the wide variability due to the combination of the aforementioned factors, it is difficult to obtain an accurate comparison between the different previous research works.

Photosynthesis and stomatal conductance

The photosynthetic rate was quantified in terms of CO_2 assimilation rate (Figure 2a); the assumptions of normality and homoscedasticity were verified (p= 0.053 and p= 0.065, respectively), resulting in an effect size of η^2= 0.32; the Anova test ($F_{4,10}$= 7.8, p= 3.1x10^{-5}) indicated that at least one of the means of the treatments was different; the data showed a higher photosynthetic rate in the LED light treatments T2 and T5, with average values of 16.9 and 17.3 (mol CO_2 m^{-2} s^{-1}), respectively.

Figure 2. a) CO_2 assimilation rate [16.29 ±0.35 ($\bar{x}$ ±SE) (mol m^{-2} s^{-1}, n= 5] and b) stomatal conductance [0.386±0.018 ($\bar{x}$ ±SE) (mol m^{-2} s^{-1}, n= 5]. Tukey HSD-based clustering with *p*< 0.05.



The reference treatment T1 and treatments T3 and T4 were the lowest in terms of photosynthetic rate values. Regarding the stomatal conductance rate, the results of the Anova ($F_{4,10}$= 7.97, p=

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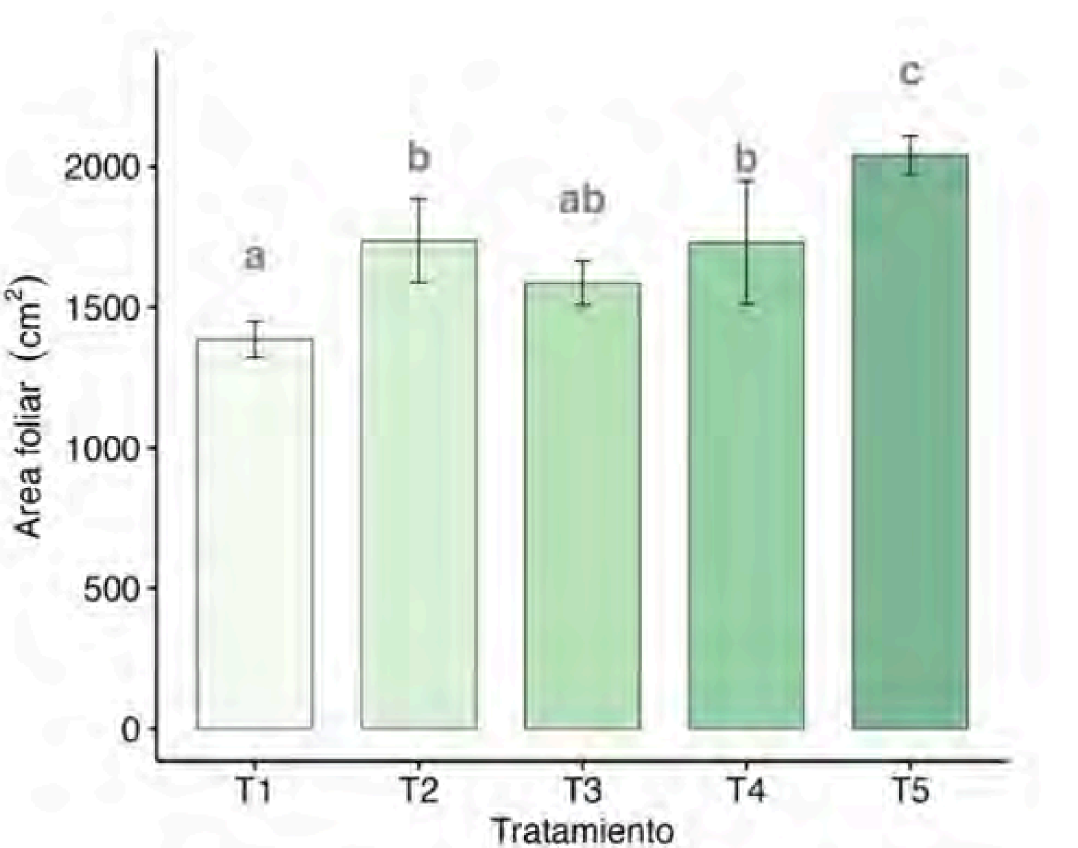
2.5 x 10^{-5}) indicated a treatment effect, with a η^2= 0.3. Treatments T2-T5, complemented with LED light, were significantly different and superior compared to the reference treatment T1 (Figure 2b), since the LED light treatments showed, on average, 18.9% higher stomatal conductance values compared to T1, with a standard error (SE) of 0.28 (mol CO_2 m^{-2} s^{-1}.

Treatments T2 to T5, having been supplemented with LED light, developed a greater leaf area (Figure 3); this possibly led to a higher photosynthetic rate by capturing a greater amount of light (Jishi, 2018). Regarding the stomatal conductance observed in the different treatments, it correlated in a directly proportional way with the rate of photosynthesis, which is observed mainly in the treatments with supplementary light (T2-T4), which generally had higher stomatal conductance and a higher photosynthetic rate compared to T1, because the stomata regulate gas exchange, including CO_2 and water vapor, which in turn affect the rate of photosynthesis (Avgoustaki *et al*., 2021b).

Figure 3. Leaf area [1696.1 ±107.44 ($\bar{x}$ ±SE) cm^2, n= 5] of lettuce plants at the end of the cycle. Tukey HSD-based clustering with *p*< 0.05.



Although Liu *et al*. (2025) used a similar intensity, 210 (mol m^{-2} s^{-1}, they observed a decrease in photosynthetic rate; in their case, they applied R/far-R spectra with intermittency regimes of 5 to 45 min, which differ from those of the present study. On the other hand, in experiments with basil (Avgoustaki *et al*., 2021a) also found a higher rate of photosynthesis in treatments with pulsed LED light; nevertheless, it was lower when they used short periods of light, 10 min, that is, a light/dark ratio of 1:5 and they argued that with this light rate, the cells would not have enough energy to carry out their photosynthetic process.

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Growth parameters in lettuce leaves

The dimensions of young adult leaves (three per plant) were measured at the end of the crop cycle and analyzed as independent biological variables; Table 2 showed that, in terms of leaf length, treatment T3 was the only one superior to the control T1, but does not differ from the rest of the treatments with supplementary LED light. Regarding leaf width, the intermittent light treatments (T3-T5) show a tendency to increase this parameter.

Table 2. Average dimensions and standard deviation (SD) of lettuce leaves measured at the end of the crop cycle.

Treatment	Growth parameters		Leaf geometry
	Width ±SD (cm)	Length ±SD (cm)	Length/width ±SD (cm cm-¹)
T1	8.38^{a} (1.46)	20.73^{a} (1.31)	2.54^{a} (0.431)
T2	9.9^{ab} (2.28)	21.42^{a} (3.4)	2.21^{a} (0.344)
T3	11.02^{b} (1.94)	24.75^{b} (1.29)	2.29^{a} (0.348)
T4	9.85^{ab} (1.08)	22.78^{ab} (2.9)	2.32^{a} (0.208)
T5	9.96^{ab} (1.37)	22.52^{ab} (3.49)	2.29^{a} (0.429)

Values in the same column with different letters indicate the existence of a statistically significant difference between them with α= 0.05.

The implementation of the treatments did not cause alterations in leaf geometry concerning roundness or length/width ratio. In general, LED light treatments led to larger leaves than those of T1, which is consistent with the leaf area values (Figure 3), thus indicating an impact on the size of the leaves, but not on their shape. The proportion of red light used in the present experiment was 5.3 times higher than that of blue light; according to Ali *et al*. (2023), red light favors leaf expansion, a phenomenon also observed in the leaf area, which could explain the difference in leaf size of LED light treatments compared to T1.

The leaf area was determined at the end of the cycle by high-resolution images of the leafless foliage; the Anova test ($F_{4,10}$= 13.56, p= 7.15x10^{-5}) indicated a treatment effect, with an $\#^2$= 0.78; the results showed T1 with the lowest average leaf area value (1 385 cm^2), followed by treatments T2 and T4, clearly different from T1 and T5, with T5 being the treatment with the largest leaf area, reaching an average value of 2 042 cm^2, which means 21.2% more than the rest of the treatments with LED light (T2-T4).

An upward trend was observed from T3 to T5 as a function of the increase in the distribution of the LED light period over a 24-h day (Figure 3), even though the daily light integral (DLI) was lower at T5 due to a photoperiod of 15 h compared to treatments T2-T3, which had a photoperiod of 16 h.

Fresh and dry weight of the foliage

The data on the fresh and dry weights of the foliage measured at the end of the crop cycle; the Anova test for fresh weight ($F_{4,10}$= 5.81, p= 0.0049) and dry weight ($F_{4,10}$= 3.22, p= 0.042) with a $\#^2$= 0.61 and $\#^2$= 0.46 for fresh and dry weight, respectively; both showed treatment effects and had a similar behavior (Figure 4); therefore, the dry and fresh weights in T1 were statistically lower compared to T5, with average values of 70.6 g and 103.6 g of fresh weight, respectively; it was also observed that there was no difference between treatments T2 to T4, which had a similar net photoperiod of 16 h.

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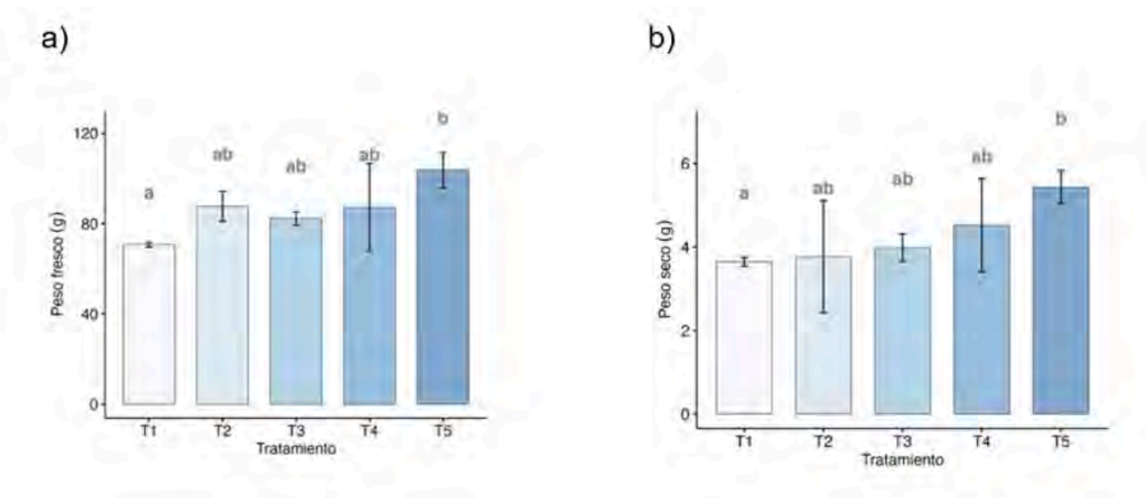
Figure 4. a) fresh weight of the foliage [86.3 ±5.31 (±SE) g, n= 5] and b) dry weight of dried foliage (4.27 ±0.32 (±SE) g, n= 5). Tukey HSD-based clustering with *p*< 0.05. $\bar{x}$



Treatments with larger leaf area (Figure 3) also consistently showed higher values of fresh weight (Figure 4a), which is consistent with the expectation that a larger photosynthetic surface area implies a greater accumulation of biomass; Boros *et al*. (2023) mention that a linear increase in DLI led to an increase in biomass; these same authors suggest that the effect can vary as a function of factors such as DLI, photoperiod, leaf area, and light intensity and quality.

The results of the present study contrast with the mentioned above, since treatment T5, with a photoperiod of 15 h, that is, one hour less than the rest of the treatments with supplementary LED light, showed an average value of 103.6 g of fresh weight, being higher than the control T1, which reached an average of 70.6 g, but statistically similar to T2-T4, possibly due to the effect of intermittent light application in an on/off ratio of 2:1 (30 min/15 min).

This is consistent with the findings by Avgoustaki *et al*. (2021b), who worked with basil plants under longer periods of darkness and shorter periods of light (6:1), combined with continuous LED light on the same day, and found higher biomass production in treatments with intermittent light compared to continuous light. Similarly; Chen and Yang (2018) found an increase in biomass in lettuce plant shoots by implementing intermittent periods of light in ratios of 2:1 (light/dark) with on/off configurations of 8 h/4 h, 4 h/2 h, and 3 h/1.5 h using only R:B spectra at a PPFD intensity of 200 µmol m^{-2} s^{-1}.

The effect on growth in lettuce plants that can be produced by the vast diversity of possible combinations of factors such as photoperiod, light intensity and quality, and the type of spectrum and the different proportions of RGB light, makes it challenging to make an accurate comparison between previous research and these results.

A statistically significant increase in leaf area (cm^2), fresh weight (g), and CO_2 assimilation rate (µmol m^{-2} s^{-1}) was observed in the treatments with supplementary LED light compared to the control ($F_{4,10}$= 7.8, p= 3.1x10^{-5}); in contrast, the leaf shape index (length/width) did not show significant differences. Nonetheless, Nissim-Levi *et al*. (2019) studied chrysanthemum plants with pulsed light and found that blue light inhibited flowering and that the use of pulsed red light alone led to shorter stems compared to plants with continuous light.

On the other hand, Ali *et al*. (2024) report that the use of intermittent light at high frequency (1 KHz) caused a significant reduction in the fresh weight of green and red lettuce when using only artificial light with a photoperiod of 16 h, which contrasts with the results of the present study, which could indicate that short and not high frequency intermittency periods could be more beneficial for the vegetative growth of lettuce plants.

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In their study, Chen *et al*. (2017) found higher biomass production in lettuce grown with continuous LED light in an R:B ratio of 2:1 compared to treatments irradiated with RB light with an alternating power-on mode in 1:1 time ratios, that is, when light R was on, light B remained off, and after a specific time, they exchanged state from on to off and vice versa, thus testing different time lapses, from 4 h to 1 h, and in their results, they show that the simultaneous application of RB leads to greater biomass, as applied in the present study.

Regarding the parameters evaluated, treatment T5 did not show a significant difference compared to the rest of the treatments with LED light (T2-T4), except in leaf area; it is possible that extending the supplementary light hours could enhance and show more the effects and differences; bearing in mind that T5 operated with one hour less without negatively affecting the leaf area, photosynthesis, and fresh and dry weight, the application of pulsed LED light with short on/off periods could be then considered as a recommendable alternative for artificial lighting systems, with the consequent advantage of providing a reduction in operating time (25%) without reducing lettuce growth.

The effect of using supplemental LED light could be different depending on the time of year, as stated by Tewolde *et al*. (2016), who found a significant effect on tomato production when using supplemental LED light in autumn and winter, possibly due to differences in the amount of natural light influenced by latitude. Ohtake *et al*. (2018) mention that using pulsed LED light and alternating the R and B spectra accelerates the growth of lettuce plants, especially between 21 and 31 days after sowing; this is possibly an indication that the mode of application of the LED light, whether it is continuous, intermittent or alternating, should be adjusted depending on the stage of development of the crop.

Among the limitations of the present study are the use of a single variety of lettuce, a relatively small sample size, and the fact that this study was carried out only in an autumn period; this last point could be considered a relevant factor because most of the DLI comes from sunlight and can be widely affected by the seasons of the year.

Conclusions

The RGB LED light in a 16:1:3 ratio, supplied in addition to natural light intermittently at 30/15 min (on/off) intervals to lettuce plants of the Paris Island variety under a multi-tunnel greenhouse at night in autumn, does not cause significant differences (Anova, $p > 0.05$) in photosynthetic rates, stomatal conductance, or fresh or dry weight between the pulsed and continuous complementary LED light. The intermittent light (30/15 min) produces a statistically significant increase (Anova, $p = 7.15 \times 10^{-5}$) in terms of leaf area compared to the continuous LED light, allowing a 25% reduction in the operating time of the lighting system without negatively affecting this parameter.

Bibliography

1 Ali, A.; Santoro, P.; Ferrante, A. and Cocetta, G. 2023. Investigating pulsed LED effectiveness as an alternative to continuous LED through morpho-physiological evaluation of baby leaf lettuce (*Lactuca sativa* L. var. Acephala). South African Journal of Botany. 160(3):560-570.

2 Ali, A.; Santoro, P.; Ferrante, A. and Cocetta, G. 2024. Continuous and pulsed LED applications on red and green lettuce (*Lactuca sativa* L. var. capitata) for pre- and post-harvest quality and energy cost assessments. Sci Hortic. 338:1-24.

3 Avgoustaki, D. D.; Bartzanas, T. and Xydis, G. 2021. Minimising the energy footprint of indoor food production while maintaining a high growth rate: introducing disruptive cultivation protocols. Food Control. 130:1-13.

4 Boros, I. F.; Székely, G.; Balázs, L.; Csambalik, L. and Sipos, L. 2023. Effects of LED lighting environments on lettuce (*Lactuca sativa* L.) in PFAL systems a review. Sci Hortic. 321:1-19.

DOI: https://doi.org/10.29312/remexca.v16i30.4044

5 Burattini, C.; Mattoni, B. and Bisegna, F. 2017. The impact of spectral composition of white leds on spinach (*Spinacia oleracea*) growth and development. energies (basel). Energies 10(9):1-14.

6 Chen, X. L. and Yang, Q. C. 2018. Effects of intermittent light exposure with red and blue light emitting diodes on growth and carbohydrate accumulation of lettuce. Sci Hortic . 234:220-226.

7 Chen, X. L; Yang, Q. C.; Song, W. P.; Wang, L. Ch.; Guo, W. Z. And Xue, X. Z. 2017. Growth and nutritional properties of lettuce affected by different alternating intervals of red and blue LED irradiation. Sci. Hortic. 223:44-52. https://doi.org/10.1016/j.scienta.2017.04.037.

8 Chinchilla, S; Izzo, L. G.; Van-Santen, E. and Gómez, C. 2018. Growth and physiological responses of lettuce grown under pre-dawn or end-of-day sole-source light-quality treatments. Horticulturae. 4(2):1-10.

9 Dutta-Gupta, S. 2017. Light emitting diodes for agriculture: smart lighting. In light emitting diodes for agriculture: smart lighting. 1st . Ed. 113-147 pp. Springer. https://doi.org/10.1007/978-981-10-5807-3

10 He, D.; Kozai, T.; Niu, G. and Zhang, X. 2019. Light-emitting diodes for horticulture bt - light-emitting diodes: materials, processes, devices and applications. *In*: Li, J. and Zhang, G. Q. Ed. Springer International Publishing, Cham. 513-547 pp.

11 Jishi, T. 2018. LED lighting techniques to control plant growth and morphology. *In*: smart plant factory: the next generation indoor vertical farms. 211-222 pp.

12 Jishi, T.; Kimura, K.; Matsuda, R. and Fujiwara, K. 2016. Effects of temporally shifted irradiation of blue and red LED light on cos lettuce growth and morphology. Sci Hortic . 198:227-232.

13 Nissim-Levi, A.; Kitron, M.; Nishri, Y.; Ovadia, R.; Forer, I. and Oren-Shamir, M. 2019. Effects of blue and red LED lights on growth and flowering of Chrysanthemum morifolium. Sci Hortic . 254:77-83.

14 Ohtake, N.; Ishikura, M.; Suzuki, H.; Yamori, W. and Goto, E. 2018. Continuous irradiation with alternating red and blue light enhances plant growth while keeping nutritional quality in lettuce. HortScience. 53(12):1804-1809.

15 R Core Team, 2023. R: a language and environment for statistical computing (4.2.3) R. Foundation for Statistical Computing. https://www.r-project.org/,

16 Radetsky, L.; Patel, J. S. and Rea, M. S. 2020. Continuous and intermittent light at night, using red and blue LEDs to suppress basil downy mildew sporulation. Hort. Science. 55(4):483-486.

17 Reis, M. G. and Ribeiro, A. 2020. Conversion factors and general equations applied in agricultural and forest meteorology. Agrometeoros. 27:227-258.

18 Sullivan, G. M. and Feinn, R. 2012. Using effect size or why the P value is not enough. J. Grad. Med. Educ. 4(3):279-282.

19 Tewolde, F. T.; Lu, N.; Shiina, K.; Maruo, T.; Takagaki, M.; Kozai, T. and Yamori, W. 2016. Nighttime supplemental LED inter-lighting improves growth and yield of single-truss tomatoes by enhancing photosynthesis in both winter and summer. Front Plant Sci. 7:1-10. https://doi.org/10.3389/fpls.2016.00448.

20 Viršilė, A.; Brazaitytė, A.; Vaštakaitė-Kairienė, V.; Miliauskienė, J.; Jankauskienė, J.; Novičkovas, A.; Laužikė, K. and Samuolienė, G. 2020. The distinct impact of multi color LED light on nitrate, amino acid, soluble sugar and organic acid contents in red and green leaf lettuce cultivated in controlled environment. Food Chem. 310:1-9.

21 Yang, J.; Song, J. and Jeong, B. R. 2022. Lighting from top and side enhances photosynthesis and plant performance by improving light usage efficiency. International Journal of Molecular Sciences. 23(5):1-25. https://doi.org/10.3390/ijms23052448.

Effect of supplementary pulsed LED light on lettuce growth under a greenhouse

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