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Original article – Thematic Issue

Reducing the energy footprint and enhancing the flexibility of indoor growing systems while maintaining a high growth rate: Examination of disruptive cultivation protocols

D.D. Avgoustaki, N. Maras, E. Efstathiou, V. Taxakis, A. Giakoumatos and T. Bartzanas
Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens, Athens, Greece

Summary

Most of the selected cultivated species in vertical farms, specifically leafy vegetables, require multiple hours of photoperiod to reach their full potential in terms of biomass, leaf size, nutritional value, taste, and color. At the same time, the cost of electricity can be very high due to the many hours of operation and the intense light provision which could be an inhibiting factor for the sustainability status of technology and at the same time jeopardize the financial viability of the farm. In this study, we tested the growth of *Valerianella locusta* plants under continuous and interrupted photoperiodic light intervals. The leaf physiological traits of two different photoperiod treatments were assessed and used to estimate the toleration rate of the plants under different lighting schemes. In the first indoor growth chamber, plants were grown under 14 h of continuous light while in the second chamber under a normalized photoperiod of 14 h with intermittent light intervals of 10 min of light followed by 50 min of dark and 4 of continuous light intervals. The purpose was to examine, assess and design flexible disruptive light exposure to reduce the compact electricity consumption for crops grown in indoor environments with more flexible protocols while maintaining a high growth rate and biomass production of the plants. The presented results of this experiment shows a positive correlation of the plants' responses to abiotic stress when exposed to short light periods of disruptive light, without having significant effects on the physiological responses of the crop. Postharvest measurements revealed that plants under intermittent lighting protocols produced almost double fresh and dry biomass compared to plants under continuous photoperiod, while operated under a more flexible lighting schedule that could act as a load shifted energy demand response units and operated under the most profitable and ecological energy schemes.

Keywords
Valerianella locusta, vertical farms, intermittent light, photoperiod, chlorophyll, biomass production, energy demand

Significance of this study

What is already known on this subject?

- Light is one of the most crucial environmental factors that highly affects plant growth and development. Plants grown in indoor environments can highly perform and yield when exposed to a reduced photoperiod with intermittent light. However, there is a need for utilities to provide hours of low electricity prices during daytime hours, which would help the growers organize the operation of their lighting equipment in standard time intervals. This is why we decided to study the response of plants under a system in which light was emitted when both energy demand and electricity prices were low.

What are the new findings?

- This paper research a light methodology in which the time intervals of intermittent lighting are provided to cherry tomato plants based on the fluctuating electricity prices of the energy market. This is the first study that examines the reaction of plants that are cultivated for their fruit production. Data collection and analysis showed that by selecting a precise and small light interval for disruptive photoperiod that is applied and during critical photoperiod phase, tomato plants can continue their development and growth rate and develop sufficient amount of fresh production under a significantly lower electricity demand.

What is the expected impact on horticulture?

- The proposed methodology can significantly improve the energy use efficiency of the system and consequently the sustainability and profitability of vertical farms by maintaining a high production volume and a lower energy demand for the operation of the lighting systems.

Introduction

The continuously growing population in the world is major impacting the global food demand for fresh, nutritious and safe food sources. Simultaneously, FAO (2016) reported that by 2050 the arable land will not be sufficient and fertile to cover the global food production demand as it is expected that reduction will reach one-third of land requirement per person compared to the amount that was available in previous years. This phenomenon will keep evolving due to the continuous climate change and hazardous effects that impact food production such as land degradation, water pollution, deforestation, rise of temperature and poor farming practices in combination with the rapid increase of population and urbanization.

Vertical farming is a novel agricultural system that applies controlled-environment agriculture techniques (CEA) for indoor crop production maximizing crop production per year and per occupied land use with high quality, freshness, and safety standards for local consumers. Vertical farms (VFs) are equipped with soilless cultivation systems (mainly hydroponics or aeroponics), and advanced heating/cooling/ventilation (HVAC) systems that provide uniform desired cultivation conditions and usually their products are addressed to urban and/or peri-urban consumers. Thus, due to shading effects from surrounding buildings in the urban network, VFs may have limited access to sunlight radiation and for this reason, artificial lighting sources, mainly LED lamps are the main source of light radiation. Light plays a crucial role in the growth and developmental processes of plants as it activates the process of photosynthesis. Modifying one or more of its main properties, light quality (spectrum selection), light quantity (intensity) and light duration (photoperiod) can influence the growth rate, physiology, morphology, taste, nutrient status and color of crops.

For indoor farming facilities that use artificial light, the definition of the exact light recipe and management is a significant factor that influences both the crop production and the economic and sustainability status of the farms, taking into consideration that lighting operation consists approximately 40% of the total operational expenses of the VFs (Avgoustaki and Xydis, 2020).

Photoperiodism has a particular impact on leafy vegetables' production as day length manipulation could promote the development and growth rate of plants specifically during flowering, fruiting, stem elongation and biomass production (Mattson and Erwin, 2005). The photoperiodic regulation when combined with air temperature could prolong the vegetative stage of plants and regulate flowering responses as is required in order to meet the production demand and the desired harvest timing. Specifically, the structure of plants is partially regulated by the signals of light they receive in their growing environment, while photosynthesis forms up to 95% of yield production and is highly dependent on the properties of the light source (Dong et al., 2015). Apart from photosynthesis, light characteristics have a major effect on plants' morphology and other reactions via the activation of different photoreceptors. Photoreceptors are light responsive mechanisms of plants that control the expression of specific genes that affect the development and growth rate as also secondary metabolism in plants (Fuglevand et al., 1996; Brian and Vince-Prue, 1997). Plants in order to adapt to different lighting environments, have obtained various mechanisms that include morphological and physiological responses at leaf level (Zhang et al., 2022). Plants by adapting processes can maximize available light capture and meet the demand to enhance and promote their photosynthetic capacity (Steinger et al., 2003; Dong et al., 2015).

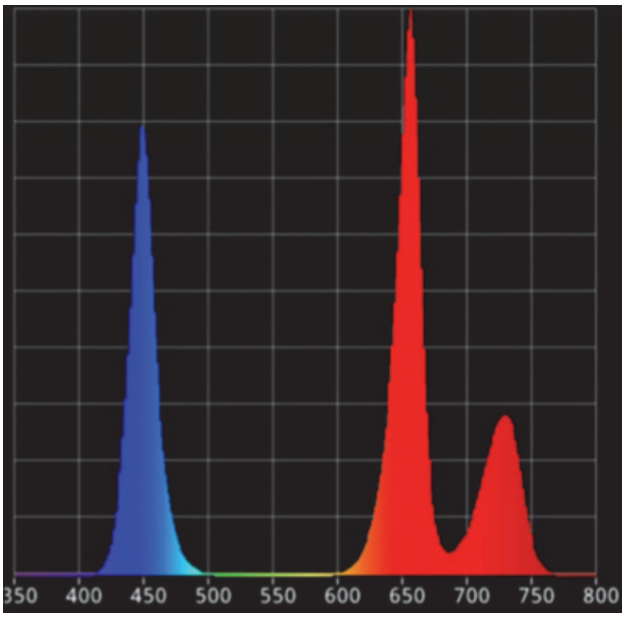


Figure 1. Relative spectral emission of the LED lamp (AstroPlant LED panel, The Netherlands) used in the experiment and measured with the spectrometer uSpectrum.

Based on previous research (Matthijs et al., 1996; Avgoustaki et al., 2021; Avgoustaki et al., 2020) longer dark periods during daytime tend to decrease growth rate of plants. However, a decrease in light flux under interrupted light seems to reduce the growth rate less than in the case of a similar flux decrease under a continuous lighting system. Intermittent light is a technique that allows us to evaluate plants' non-photochemical reactions, which are correlated with the reduction of photochemical reactions (Briggs, 1935). In other words, during intermittent light, the light is emitted intermittently in short cycle periods. The ultimate goal of using interrupted light is to design a control energy system per growth cycle caused by saturation of the photochemical reaction. Intermittent light helps define the relationship between photochemical and non-photochemical plants' reactions that are connected with the photoperiod. As mentioned light operation has a major impact on the economic viability and sustainability of VFs due to the intense operation demand both in terms of intensity and duration. Therefore, there is a high demand to examine and develop energy-saving strategies for LED operation in indoor farming facilities to reduce the bankruptcy risk of the farms and improve their environmental performance for local fresh food production. Countries that participate in fluctuations of electricity prices could benefit from different electricity prices at different times of the day and therefore, organize the production during the hours with the lowest electricity prices and avoid expensive hours in order to minimize the energy costs. However, fluctuating energy grids do not usually offer continuous low electricity prices and therefore, the implementation of precise load-shifted production for indoor farms becomes more complicated.

The goal of this research is to study and evaluate the responses of *Valerianella locusta* plants under a photoperiod of 14 h in total, however in the control case, light is delivered continuously to plants, while in the stress case, plants are exposed to intermittent light intervals. The upper purpose of this study is to examine the possibilities of a lighting system that operates under the influence and advantage of fluctuating electricity market and shifts demand response to minimize the total energy costs without having a negative impact on the growth and development rate of plants.

Material and methods

Experimental set up

The experiment was conducted in two identical indoor growth chambers (Chamber A and Chamber B) that were installed in the Laboratory of Farm Structures at the Agricultural University of Athens, Greece. Both chambers were operating with controlled conditions of air temperature (T_air) and the relative humidity (RH%), set at 25°C and

55%, respectively and CO_2 at 400 ± 50 ppm. The external dimensions of the climate chambers were the following: height 200 cm, width 82 cm, and length 72 cm, while the internal dimensions of the chambers were: height 140 cm, width 60 cm, and length 60 cm. The growing area in each chamber was 30 (W) × 20 (L) × 40 (H) cm. The climate growth conditions in the chambers, including T_air, RH%, and CO_2 concentration, were automatically monitored and controlled using a climate control sensor (Astroplant, The Netherlands), one in each chamber throughout the experimental period. The light radiation provided in each chamber was sourced from two identical LED lamps (AstroPlant LED panel, The Netherlands) placed at the top of the chamber. The spectrum specifications of LED lamps were the following: 8 single-photon counting (SPC) of red peaking at 650 nm, 4 SPC of blue peaking at 450 nm, and 4 SPC of near-infrared (NIR) peaking at 730 nm (Figure 1). When LED was switched on, the amount of photons, reaching the plant canopy expressed in photosynthetic photon flux density (PPFD) was maintained at 250 mmol m^{-2} s^{-1} for both chambers with a stable Daily Light Integral (DLI) at 11.5 mol * m^{-2} * day^{-1}. Daily measurements were taken with a spectroradiometer from uSpectrum (UPRteck/LI-COR) in order to monitor the spectral dimensions during the experiment.

Valerianella locusta plants were selected as cultivars of examination in this research study. *Valerianella* belongs to the family *Caprofoliaceae* and consists of a leafy vegetable with high nutritional value, small compact size, small growth cycle, with high purchase value characterizing this crop as an interesting option for indoor vertical cultivation with artificial light.

In each chamber, 4 seedling plants were transplanted, 3 weeks after sowing. Plants were growing in a Deep Flow hydroponic technique in rockwool substrate. Water and nutrient solution were applied to all plants as presented in Table 1.

Table 1. Nutrient solution applied in hydroponic *Valerianella locusta* plants (retrieved from Nutrisense).

	Value	Index
Electrical conductivity	2.50	dS/m
pH	5.6	
$Ca(NO_3)_24H_2O$	994	g
KNO_3	210.58	g
Fe-EDDHA (6% Fe)	23.2	g
$MgSO_4 \cdot 7H_2O$	418.71	g
KH_2PO_4	204.1	g
K_2SO_4	210.65	g

The photoperiod for *Valerianella* plants in Chamber A (control treatment) was set at 14 h of continuous photoperiod followed by 10 h of continuous dark and light intensity 250 PPFD (in µmol m^{-2} s^{-1}) as was evaluated from previous experimental sessions (Avgoustaki et al., 2023) that is the most beneficial for indoor cultivation of *Valerianella* plants in terms of energy use efficiency (energy consumption × biomass production) as also leaf elongation and leaf area. In Chamber B (stress treatment) plants received intermittent light intervals summing in 14 h of total daily light provision. Specifically, 4 h of continuous light followed by 4 h of darkness with 10 min of light per every dark hour (50 min of dark). The examined lighting schedule was applied after the transplanting into Chamber B (Figure 2).

Data collection

Measurements started when plants had developed two fully developed leaves. For one week all plants in both chambers received the same photoperiod at 14 h of continuous light followed by 10 h of continuous dark. After this week, the intermittent lighting treatment was applied on Chamber B.

Chlorophyll content measurements were taken daily manually from young and fully developed leaves from each plant with a portable chlorophyll sensor (CCM –200plus, OPTISciences, Inc., U.S.A. (CCI unit). The input of electrical energy was measured using a power and energy logger, PEL 103 Chauvin Arnoux. The electrical energy consumed for the *Valerianella* production was measured for each growing treatment, taking into account the total leaf fresh and dry biomass produced by the eight plants, the plant size in each treatment, the photoperiod (hours of light), and the energy consumed by the system per hour. The result is presented in kWh kg^{-1}. Shoot fresh weight measurements were taken separately for stems and leaves. For the dry weight measurements, the parts of plants were placed in a dry oven at 80°C for 48 h, during which all the water evaporated.

Statistical analysis

Data were subjected to an independent-samples *t*-test, including if they followed Levene's test for homogeneity of variances. The analyses were performed using SPSS for Windows (IBM Statistics for Macintosh, v. 25.0).

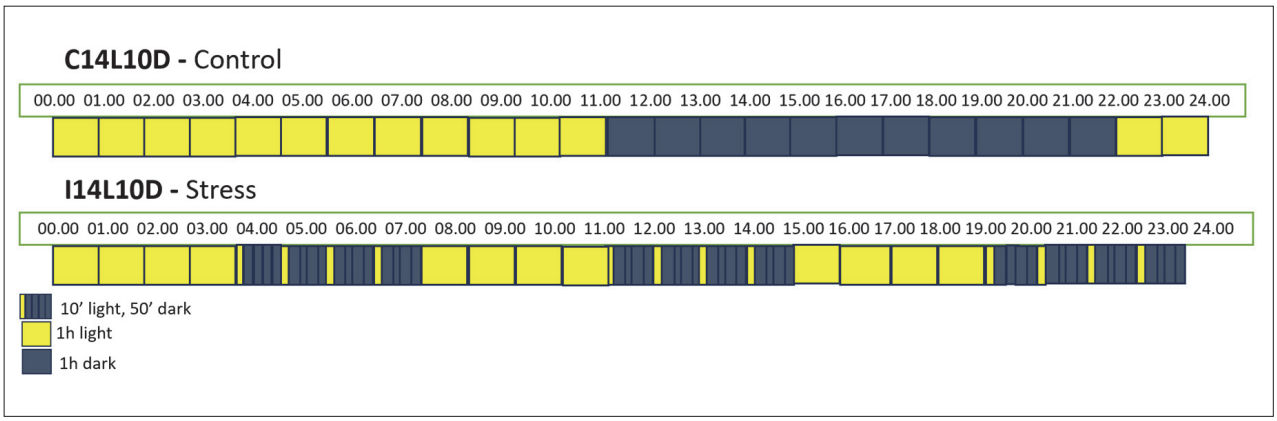


Figure 2. Graphical representation of the light schedules in each chamber. A: Control treatment (C14L10D) with 14 h of continuous light and 10 h of continuous darkness. B: Stress treatment (I14L10D) with 4 h of continuous light followed by 4 h of darkness with 10 min of light per hour of darkness.

Null hypothesis

There is no significant difference in the growth and development rate of *Valerianella locusta* plants that grow under different light treatments of continuous and intermittent photoperiod.

Results

Statistical analysis of chlorophyll content

Figure 3a presents the total average chlorophyll content of plants under the two different photoperiodic treatments. The line graph shows that plants initially had the same dynamic of chlorophyll content formation, however after the first 10 days the difference between the control treatment, C14L10D (M = 41.6, SD = 2.1) started increasing and at day 13 of the experiment, the intermittent treatment, I14L10D (M = 38.4, SD = 1.1) became statistically significant lower compared to the control at t (33.653) = 6.423, p = <.001.

As described in the methodology section of this study, the chlorophyll content was measured five times per day. The chlorophyll content was measured separately under the 10-min light intervals with limited radiation as also at the end of the continuous light treatment, where plants had sufficient time to receive, absorb and process more light radiation and convert electrical energy into chemical energy via the process of photosynthesis. Therefore, the statistical analysis was conducted for both the data sets under the continuous light (4 h) and the intermittent light intervals (10 min).

Under the 4 h of continuous photoperiod, the chlorophyll content under the control treatment, C14L10D (M = 39.9, SD = 1.64) did not present any statistically significant differences from the stress treatment, I14L10D (M = 38, SD = 1.4), at t (44) = 4.185, p = 0.287.

Subsequently, the chlorophyll content under the intermittent light intervals was measured and analyzed showing that the control treatment, C14L10D (M = 43.4, SD = 3) was statistically significant higher compared to the plants under the intermittent light treatment, I14L10D (M = 38.9, SD = 1.8) from day 13, at t (35.326) = 6.045, p = <.001.

These results indicate that there is a significant effect on chlorophyll content (and potentially on photosynthetic efficiency since chlorophyll is one of the main indicators of photosynthetic capacity) from intermittent radiation. Additionally, from these results, it is observed that plants under intermittent radiation continued their development rate under the 4-h photoperiodic light interval at a steady pace similarly to plants grown under continuous photoperiod while they responded negatively to small light intervals of 10 min that also has an impact on the overall performance of chlorophyll content formation in the timeline sequence.

Post-harvest assessment of *Valerianella locusta* plants under continuous and intermittent lighting treatment

The duration of the experiment lasted for 23 days for both treatments until plants reached their full size in a growth cycle. Fresh and dry weight (FW and DW, respectively) was measured as also the fresh and dry biomass in order to define the total yield production for the two different chambers. Leaf area (LA in cm^2) was measured at the end of the experiment showing that plants grown under the intermittent photoperiod present an increase at 59%, yet non-statistically significant compared to the control treatment (Table 2). On the contrary, in terms of the size of plants (Rosette's diameter in cm), it becomes clear that plants under the intermittent photoperiod, I14L10D (M = 18.5, SD = 0.8) were statistically

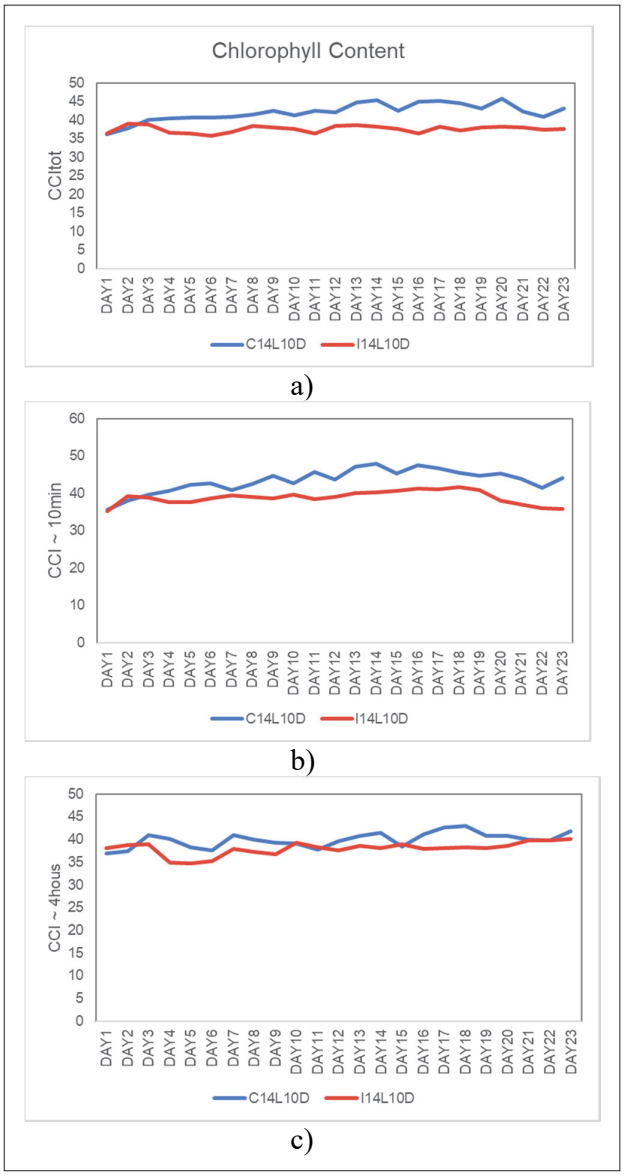


Figure 3. Average daily evolution for healthy plants, i.e., C14L10D (blue line) and stressed plants I14L10D (red line). a) presents the total average daily chlorophyll content between the two different treatments; b) presents the average chlorophyll content under the 10-min light intervals between the two treatments; and c) presents the chlorophyll content under the 4-h light intervals between the two treatments.

significant bigger compared to the continuous photoperiod, C14L10D (M = 12.2, SD = 2.9), at t (6) = -4.244, p = .005 (at significant p-value <.05).

The total biomass of the plants in each treatment was estimated by the following equation:

$$\text{Fresh biomass (g m}^{-2}) = \text{FW (g)/growing area (m}^2) \quad (1)$$

$$\text{Dry biomass (g m}^{-2}) = \text{DW (g)/growing area (m}^2) \quad (2)$$

where the growing area was 0.5 m^2 for each growing plot.

Measurements showed that plants under intermittent photoperiod developed significantly increased fresh mass (M = 8.68, SD = 1.5) compared to the continuous photoperiod (M = 5.12, SD = 1.1) at t (6) = -3.830, p = .009. Similarly the dry mass of plants at the I14L10D treatment (M = 0.97, SD = 0.2)

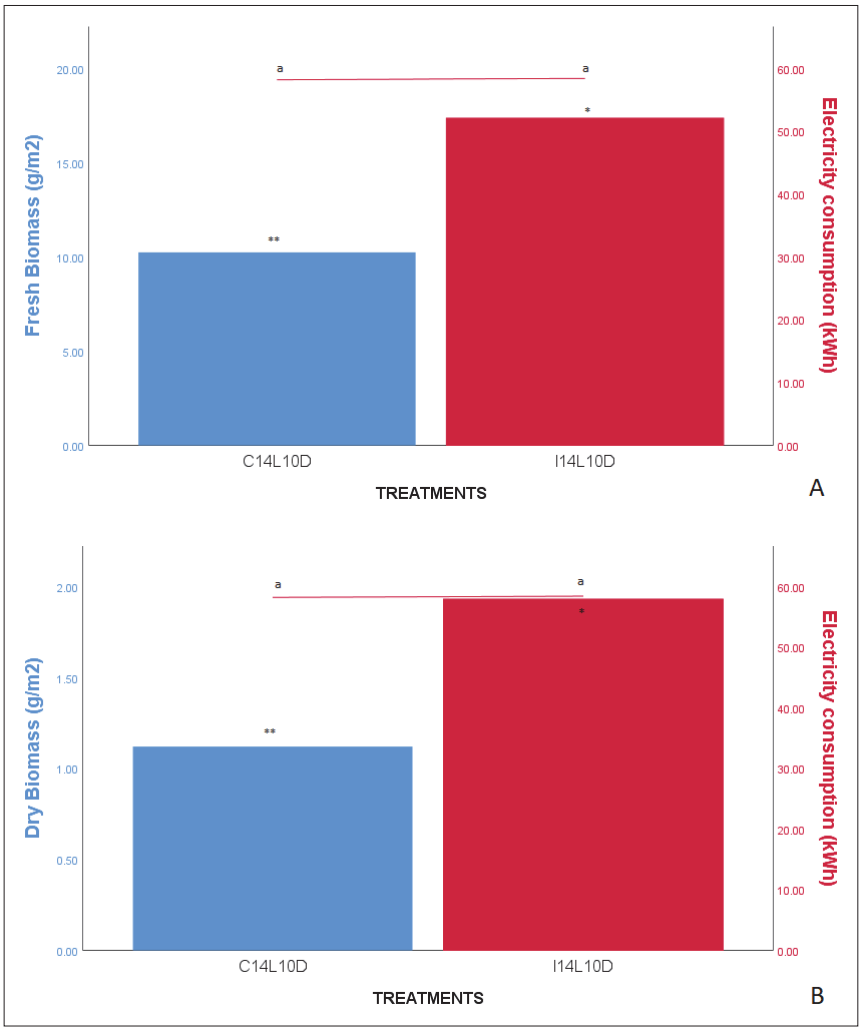


Figure 4. A: The left axis (histograms): The average shoot dry weight (g). The right axis (line): The average electrical energy consumption to produce *Valerianella* (kWh) grown under the two light treatments. B: The left axis (histograms): The average shoot dry weight (g). The right axis (line): The average electrical energy consumption to produce *Valerianella* (kWh) grown under the two light treatments. Different letters and annotations indicate significant differences between treatments ($p < 0.05$).

Table 2. Results of statistical analysis comparing the quantitative mean values of the two treatments C14L10D (control) and I14L10D (stress). The columns represent the sample size (N), mean values (Mean), standard deviation (SD) and level of significance (p-value). Significant at the $p < 0.05$ level.

	Treatments	N	Mean ± SD	p-value
Diameter (cm)	C14L10D	4	12.2 ± 2.9	0.009
	I14L10D	4	18.5 ± 0.8	
LA (cm^2)	C14L10D	4	112 ± 36.4	0.105
	I14L10D	4	178 ± 27.4	
Fresh weight (g)	C14L10D	4	5.12 ± 1.1	0.025
	I14L10D	4	8.68 ± 1.5	
Dry weight (g)	C14L10D	4	0.56 ± 0.2	0.05
	I14L10D	4	0.97 ± 0.2	
Fresh biomass (g m^{-2})	C14L10D	4	10.24 ± 2.1	0.009
	I14L10D	4	17.36 ± 3	
Dry biomass (g m^{-2})	C14L10D	4	1.12 ± .49	0.05
	I14L10D	4	1.93 ± .45	

was significantly higher compared to the C14L10D treatment ($M = 0.56$, $SD = 0.2$), at $t(6) = -2.446$, $p = .050$, showing a high impact of intermittent light intervals at the final harvested yield and consequently the salable part of the crops.

From both Figure 4 it is observed that the energy demand was identical for both treatments since in both chambers the total light was set at 14 h daily, while it was distributed under interrupted light intervals. Non withstanding the above, in Figure 4a it is observed that fresh biomass production was significantly higher under the I14L10D treatment ($M = 17.36$, $SD = 3$) compared to the C14L10D treatment ($M = 10.24$, $SD = 2.1$) presenting an increase of 40%, at $t(6) = -3.830$, $p = .009$. Similarly independent samples *t*-test showed that dry biomass production was significantly lower under the continuous photoperiod ($M = 1.12$, $SD = .49$) compared to the intermittent photoperiod ($M = 1.93$, $SD = .45$), at $t(6) = -2.446$, $p = .050$, indicating a profound effect of small and repeated light intervals to plants.

Discussion

The main goal of this research was to investigate the sustainability and extend the potential of applicability of indoor vertical farms with similar energy footprint but higher flexibility for more affordable and ecological production of crops for urban consumers. In VFs the vast majority of energy demand is distributed for artificial lighting operation, reaching almost 60–80% of the total electricity consumption of the facilities (Avgoustaki and Xydis, 2020), categorizing it as the most costly demanding process for indoor food production and consequently requiring the most urgent optimization protocols to improve the overall sustainability of the systems. Thus, increasing the flexibility and reducing the light provision (photoperiod) (Avgoustaki, 2019) without negatively affecting the growth and development rate of plants, can lead to important savings in the operational expenditures of VFs.

The purpose of this study was to examine the optimization of lighting conditions for growing the leafy vegetable of *Valerianella locusta* by alternating the light from a continuous to an interrupted flow and at the same time identify the responses of plants to the different light treatments. To be more specific, it examines the influence on chlorophyll content as well as various morphological and quantity characteristics of the plants between two different treatments as well as if and for how long we could shift the energy demand response to more cost-effective electricity consumption without having a negative influence on the yield production.

Abiotic factors such as water, light, nutrients and CO_2 as also physiological factors such as chlorophyll content and stomatal conductance have a strong impact on the photosynthetic activity of plants and their growth rate. In this study, the chlorophyll content was examined as one of the main indicators of photosynthetic efficiency of plants in order to detect plants' responses to intermittent radiation.

Light is one of the main factors that influence the growth of green species as well as the production and subsequently the biomass volumes. Plants' responses to light provoke physiological alterations that can affect the CO_2 assimilation and gas exchanges in the plants (Gonçalves et al., 2008). Therefore, it is very important to examine the reaction of plants in terms of the chlorophyll content under continuous and intermittent light intervals, since it is used as growth indicator for the phenological and physiological developmental stages of plants (Tanaka and Tanaka, 2000). Based on Grobbelaar et al. (1996), longer and continuous periods of darkness do not necessarily lead to higher photosynthetic efficiencies. Additionally, according to Iluz et al. (2012), plants absorb all the necessary light during the light period (gross photosynthesis) and continue to use it during the dark period. As it is observed in Figure 3, there was a significant reduction in chlorophyll content under the 10-min light duration which could be explained by the fact that plants' cells were not able to absorb enough electromagnetic radiation from the lamps in only 10 min to meet their metabolic requirements. However, under the 4-h light period, cells managed to process enough light energy and absorb a sufficient amount of light via chloroplasts without affecting their primary production. Further research would be necessary to uncover the dark periods under a load-shifted energy demand response lighting schedule and not only under normalized interrupted light intervals (Avgoustaki et al., 2021; Avgoustaki et al., 2020).

According to Adams et al. (1999), during short-term photoacclimation (seconds to minutes), a heat dissipation of the excess excitation energy through carotenoids was observed, which can influence the distribution of absorbed light energy between Photosystem I (PSI) and Photosystem II (PSII). Further research is needed to analyze the carotenoid level under intermittent light in detail. Another important point that can explain our results is the RuBisCO model, which is a useful tool for clarifying the intermittent light that can increase the photosynthetic efficiency.

The measurements of various chlorophyll pigments from chloroplasts and their analyses were used as stress indicators of high irradiance in the plants (Gonçalves et al., 2008). Based on previous literature (Tzina et al., 1987), the amount of chlorophyll accumulation in the early growth stages of the plants depends on the total radiation received by the crop, independent of the intervals during the dark period of the photoperiodic cycle. Furthermore, as previously mentioned in this study, the rate of photosynthesis for intermittent light depends on the interpolation between the dark intervals. When exposed to shorter dark intervals, plants contain larger photosystem units, i.e., large protein complexes embedded in the thylakoid membrane for absorbing and converting solar energy. Figure 3 depicts that the chlorophyll pigments followed an increasing rate throughout the experiment, indicating that the plants had a stable and increasing rate if they absorbed the given radiation. In the short dark periods of intermittent light, thylakoids with few and large-in-size photosystems were found, while more and smaller in size thylakoids found in the longer dark periods to maintain the same accumulation rate of chlorophyll.

Effect of different lighting systems on biomass accretion and energy demand

Photoperiod and light distribution are vital in plant biomass production, leaf size, and leaf area (Adams and Langton, 2005). In all the quantitative data that were collected with post-harvest measurements it is observed a significant positive effect of intermittent radiation. Specifically, in Table 2 it is observed that leaf area and the size of plants grown under intermittent light intervals were significantly increased which also led to significantly higher biomass production compared to plants grown under continuous photoperiod. Energy demand was identical for both treatments as the total duration of light was 14 h daily, though the distribution of light presented a higher flexibility under the intermittent lighting treatment where short light intervals can easier be provided under expensive electricity schemes and long light intervals under cheap and green energy schemes.

Conclusions

Cultivation of *Valerianella locusta* in a small-scale growth chamber under intermittent lighting showed a positive effect on the growth, development, quality, and quantity of the plants compared to the control conditions of continuous lighting. The plants grown under intermittent light had a positive effect on the final biomass production. In addition, daily measurements of chlorophyll content showed no negative results as they maintained a steadily increasing rate throughout the plants' entire growth cycle (under the 4 h light intervals) but with a more flexible electricity consumption scheme compared to the continuous lighting. The purpose of this experiment was to test the response of *Valerianella* plants under intermittent light as well as to examine their growth rate and quality using an energy efficient production system for indoor farming. The results of the experiment suggest an electricity system in vertical farms based on energy prices across

countries. The research shows that vertical farms could design their lighting system, adjusting the consumption based on low or high electricity prices. A potential taste assessment of plants under the different lighting systems would be an interesting addition to the process. Future research is needed to investigate the response of plants under various durations of intermittent light and with various LED spectrum combinations and reduced photoperiod.

Vertical farms are a great opportunity to design more sustainable systems using innovative technologies to meet the urban energy demand. However, since these systems still present new opportunities for additional energy optimization, it is crucial to develop smarter, more efficient applications and techniques, enabling vertical farms to produce high-quality products while minimizing costs.

CRediT authorship contribution statement

Dafni Despoina Avgoustaki: Data curation, Formal analysis, Writing, original draft. Maras Nikolaos: Data curation. Efstathiou Eleni: Data curation. Taxakis Vasilios: Data curation. Giakoumatos Andreas: Writing, review and editing. Thomas Bartzanas: Supervision.

References

Adams, S.R., and Langton, F.A. (2005). Photoperiod and plant growth: A review. J. Hortic. Sci. Biotechnol. *80*, 2–10. https://doi.org/10.1080/14620316.2005.11511882.

Adams, W.W., Demmig-Adams, B., Logan, B.A., Barker, D.H., and Osmond, C.B. (1999). Rapid changes in xanthophyll cycle-dependent energy dissipation and Photosystem II efficiency in two vines, *Stephania japonica* and *Smilax australis*, growing in the understory of an open Eucalyptus forest. Plant, Cell Environm. *22*(2), 125–136. https://doi.org/10.1046/j.1365-3040.1999.00369.x.

Avgoustaki, D. (2019). Optimization of photoperiod and quality assessment of basil plants grown in a small-scale indoor cultivation system for reduction of energy demand. Energies *12*, 3980. https://doi.org/10.3390/en12203980.

Avgoustaki, D.D., and Xydis, G. (2020). Plant factories in the water-food-energy nexus era: A systematic bibliographical review. Food Security *12*, 253–268. https://doi.org/10.1007/s12571- 019-01003-z.

Avgoustaki, D.D., Li, J., and Xydis, G. (2020). Basil plants grown under intermittent light stress in a small-scale indoor environment: Introducing energy demand reduction intelligent technologies. Food Control *118*, 107389. https://doi.org/10.1016/j.foodcont.2020.107389.

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*, 108290. https://doi.org/10.1016/j.foodcont.2021.108290.

Avgoustaki, D.D., Vatsola, G., Giakoumatos, A., and Bartzanas, T. (2023). Influence of different DLI treatments on *Valerianella locusta* plants grown in an indoor vertical farm. Sci. Hortic. (accepted).

Brian, T., and Vince-Prue, D. (1997). Photoperiodism in Plants (San Diego, U.S.A.: Elsevier Acad. Press). https://doi.org/10.1016/B978-0-12-688490-6.X5000-1.

Briggs, G.E. (1935). Photosynthesis in intermittent light, in relation to current formulations of the principles of the photosynthetic mechanism. Botany School Cambridge. Biol. Rev. *10*, 460–482. https://doi.org/10.1111/j.1469-185X.1935.tb00493.x.

Dong, C., Shao, L., Wang, M., Liu, H., Xie, B., Li, B., Fu, Y., and Liu, H. (2015). Photosynthetic characteristics, antioxidant capacity and biomass yield of wheat exposed to intermittent light irradiation with millisecond-scale periods. J. Plant Physiol. *184*, 28–36. https://doi.org/10.1016/j.jplph.2015.06.012.

FAO, Food and Agric. Org. of the U.N. (2016). FAOSTAT Database. www.fao.org/faostat (accessed December 1, 2016).

Fuglevand, G., Jackson, J.A., and Jenkins, G.I. (1996). UV-B, UV-A, and blue light signal transduction pathways interact synergistically to regulate chalcone synthase gene expression in Arabidopsis. Plant Cell *8*(12), 2347–2357. https://doi.org/10.1105/tpc.8.12.2347.

Gonçalves, J.F.C., dos Santos, J.U.M., and da Silva, E.A. (2008). Evaluation of a portable chlorophyll meter to estimate chlorophyll concentrations in leaves of tropical wood species from Amazonian forest. Hoehnea *5*, 185–188.

Grobbelaar, J.U., Nedbal, L., and Tichý, V. (1996). Influence of high frequency light/dark fluctuations on photosynthetic characteristics of microalgae photoacclimated to different light intensities and implications for mass algal cultivation. J. Appl. Phycol. *0921-89718*(4–5), 335–343.

Iluz, D., Alexandrovich, I., and Dubinsky, Z. (2012). The enhancement of photosynthesis by fluctuating light. In Artificial Photosynthesis, M.M. Najafpour, ed. (InTech), p. 115–134. https://doi.org/10.5772/31040.

Matthijs, H.C.P., Balke, H., Van Hes, U.M., Kroon, B.M.A., Mur, L.R., and Binot, R.A. (1996). Application of light-emitting diodes in bioreactors: Flashing light effects and energy economy in algal culture (*Chlorella pyrenoidosa*). Biotechnol. Bioengin. *50*, 98–107. https://doi.org/10.1002/(SICI)1097-0290(19960405)50:1<98::AID-BIT11>3.0.CO;2-3.

Mattson, N.S., and Erwin, J.E. (2005). The impact of photoperiod and irradiance on flowering of several herbaceous ornamentals. Sci. Hortic. *104*(3), 275–292. https://doi.org/10.1016/j.scienta.2004.08.018.

Steinger, T., Roy, B.A., and Stanton, M.L. (2003). Evolution in stressful environments II: Adaptive value and costs of plasticity in response to low light in *Sinapis arvensis*. J. Evol. Biol. *16*(2), 313–323. https://doi.org/10.1046/j.1420-9101.2003.00518.x.

Tanaka, R., and Tanaka, A. (2000). Chlorophyll is not just an accessory pigment but a regulator of the photosynthetic antenna (Sapporo, Japan: Hokkaido Univ., Inst. of Low Temp. Sci.).

Tzina, G., Argyroudi-Akoyunoglou, J.H., and Akoyunoglou, G. (1987). The effect of the dark interval in intermittent light on thylakoid development: Photosynthetic unit formation and light harvesting protein accumulation. Photosynth. Res. *14*, 241–258.

Zhang, H., Sun, X., and Dai, M. (2022). Improving crop drought resistance with plant growth regulators and rhizobacteria: Mechanisms, applications, and perspectives. Plant Commun. *3*(1), 100228. https://doi.org/10.1016/j.xplc.2021.100228.

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Address of authors:
Dafni D. Avgoustaki, Nikolaos Maras, Eleni Efstathiou, Vasilis Taxakis, Antreas Giakoumatos and Thomas Bartzanas
Department of Natural Resources and Agricultural Engineering, Agricultural University of Athens, Iera Odos 75, Athens, Greece

eJHS 89 (5)

Editorial

Vertical farms (VFs, also called Plant Factories with Artificial Lighting, PFALs) are an advanced crop production technology that allows to maximize resource-use efficiency and address food security challenges in a climate changing world, while also enabling cultivation within dense urban settings or extreme and remote environments. VF systems operate in controlled conditions, allowing for the precise regulation of all environmental factors (e.g., light, temperature, humidity, and CO_2). This results in higher yields, reduced water and mineral nutrient requirements, constant year-round production, and minimal transport-related food losses and impacts. Key technologies include LED lighting, which enhances energy efficiency while allowing to target crop-specific light needs, and recirculating irrigation and dehumidification systems that optimize nutrient and water use. Innovations such as dynamic lighting and aeroponics further improve sustainability by reducing energy consumption and environmental impact. Vertical farms also offer resilience against extreme weather and pandemics, ensuring a reliable food supply. Conversely, and despite these benefits, VFs face challenges that include high energy demands, significant initial investment, and reliance on both skilled workforce and logistical infrastructures. Solutions include integrating vertical farms with urban energy systems to reuse heat, explore renewable energy options, optimizing operational parameters with AI, and developing crop varieties tailored to controlled environments. While consumers increasingly require for fresh and sustainable products, innovative business models are also explored, as for the case of localized modular systems. Besides, as social and educational initiatives are essential for advancing uptake of VFs, training programs and participatory projects highlight the potential for improving stakeholder engagement and skills development. Moving forward, enhancing VF sustainability requires for strategies that consider the local economic, social, and environmental implications. Vertical farming holds promise for transforming agriculture, but its widespread implementation relies on technological advancements, innovative business models, and addressing geographical disparities in resource availability. This article belongs to a collection that builds on selected themes explored along the Third International Workshop on Vertical Farming (VertiFarm2024), held in Bologna (Italy) in January 2024 and attended by more than 200 delegates from 31 countries.

Giuseppina Pennisi (University of Bologna Alma Mater Studiorum)
Francesco Orsini (University of Bologna Alma Mater Studiorum)

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