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Short communication

Test of a PAR sensor-based, dynamic regulation of LED lighting in greenhouse cultivation of *Helianthus annuus*

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Summary

The intensity, and consequently the energy consumption, of light emitting diodes (LEDs) can be regulated. Therefore, LEDs can be implemented in new, dynamic energy saving strategies. Recently it has been shown that a program, which adjusts the intensity of a LED to the current solar PAR, reduced its energy consumption by 20%. The effect of a dynamic LED lighting on ornamental crops has not been tested. In this study we compared the growth of the model plant *Helianthus annuus* under a dynamic versus a static, control LED lighting. The data of this study show that the dynamic LED consumed 21% less energy than a control LED. However, there was no difference in crop quality or time to anthesis.

Keywords
energy conservation, light intensity, light quality, photosynthetically active radiation

Significance of this study

What is already known on this subject?
- A recent study has shown that application of a dynamic LED lighting reduced energy consumption, but also reduced vegetable yield.

What are the new findings?
- The dynamic LED lighting reduced energy consumption without affecting the quality or yield of sunflowers.

What is the expected impact on horticulture?
- This study provides a proof of principle that a dynamic LED lighting is applicable to floriculture.

Introduction

Horticulturists in the northern hemisphere use supplementary lightings to avoid growth limiting light conditions in the greenhouse during the winter months. Supplementary lightings consume a substantial amount of electric energy and thus, create high operational costs. Heuvelink and Challa (1989) have shown that the costs of a supplementary lighting with high-pressure sodium lamps (HPS) can exceed the additional profit. To increase the economic efficiency, most HPS lightings are switched off if the light intensity exceeds certain limits or a given daily light integral (DLI) (Albright et al., 2000). However, HPS lamps are sensitive to high switching frequencies and need time to heat up and cool down. It is therefore difficult to use HPS lamps for a dynamic regulation.

Light emitting diodes (LEDs) can be dimmed. Thus, the light intensity and, subsequently the energy consumption, can be increased and reduced instantaneously. Recently, Pinho et al. (2013) used LEDs to develop a dynamic lighting. They used a microcontroller, which was connected to a quantum sensor in the greenhouse. The microcontroller compared the current light intensity provided by the sensor with the required intensity (set point). When the solar radiation was too low, the program increased the intensity of the LEDs until the sum of the solar radiation and the supplementary light was equal to the set point. Similarly, if the solar light intensity increased, the LED intensity decreased. The authors reported that the dynamic regulation consumed 20% less energy than the control LED. However, they also reported that the fresh weight of lettuce grown under the dynamic LED was 23% lower compared to lettuce grown under the control LED. The effect of light intensity on growth and yield of vegetables depends on a variety of other factors, such as temperature, humidity and irrigation. However, as a rule of thumb growers calculated that an increase of light intensity of 1% corresponds to an increase of 0.5–1% of crop yield (Marcelis et al., 2006).

The effect of light intensity on ornamental crop yield can be very different. Many ornamental crops require a certain minimum DLI for flower initiation. Increasing the light intensity beyond this point provides little additional benefit (Buwalda et al., 2000; Mortensen, 1994). For instance, Oh et al. (2009) have shown that the time anthesis of cyclamen decreased with increasing DLIs, but remained constant when the DLI exceeded 5 mol m^{-2} d^{-1}. Similar results were obtained with other bedding plants (Faust et al., 2005; Pramuk and Runkle, 2005).

Other quality parameters such as compactness, branching, and number of flowers appear to depend on the light quality rather than the light intensity, provided that a certain minimum amount of light is given (Faust et al., 2005; Bergstrand and Schüssler, 2012; Schwend et al., 2015).

Our working hypothesis was that a dynamic lighting can be used in floriculture to reduce energy consumption without affecting crop quality or flower development. To test this hypothesis, the dynamic lighting described by Pinho et al. (2013) was applied to sunflowers. Sunflowers were chosen as model plants because vegetative and generative growth are distinct growth stages (Schneiter and Miller, 1981). The experiment consisted of two parts. In a first experiment the optimum LED set points were determined in a climate chamber. Then the system was tested under greenhouse conditions. The aim of this study was to test whether a dynamic lighting can reduce energy consumption without affecting yield of sunflowers.

Materials and methods

Plants

Sunflowers (*Helianthus annuus*) 'Pacino gold' were raised from seeds (December). Seedlings were further cultivated under artificial light provided by an HPS lamp (250 W, Son-T, Philips, The Netherlands) for 16 h at 20°C at 50 µmol m^{-2} s^{-1}. After development of the first five leave pairs (on January the 16th) the plants were placed under the LED lamps (Osram Opto-Semiconductors, Regensburg, Germany). Plants were fertilized with Ferty1 (Planta, Regenstauf, Germany). Growth was inhibited with 50 ml of a 1% (w/v) Daminozide solution to equalize the growth at an early stage.

Climate chamber experiments

Sunflowers from the greenhouse were transferred to a climate chamber (Schell GmbH, Egenhofen, Germany) to study the effect of light intensity and the ratio of red to blue light on photosynthesis. The climate chamber was adjusted to 20°C. The average relative humidity was 40%. Red and blue light were provided by the same prototype red/blue LED fixtures (Osram Opto-Semiconductors, Regensburg, Germany). Intensities and ratios of red to blue light were adjusted with a RGB controller (Conrad Electronics, Hirschau, Germany). Light intensities for photosynthesis measurements were 60, 90 and 120 µmol m^{-2} s^{-1} and ratios of red to blue were 100, 75, 50, 25 and 0%. Each light regime was applied for 5 minutes. After each cycle the light was switched off for an hour. Cycles were repeated three times. Photosynthesis was measured with a phytomonitor (Schmidt, 1998). The 8 leaf chambers were equally distributed in the plant canopy to obtain an average photosynthesis rate.

Development of a dynamic lighting system

To control the light intensity, a simple Visual Basic program was developed. It compared the readings of a quantum sensor (LI-COR Bioscience, Lincoln, NE, USA) in the greenhouse with the photosynthetically active radiation (PAR) set point and stepwise increased or decreased the LED intensity to meet the set point within an acceptable tolerance of ± 10% (Figure 1).

Testing of the dynamic lighting under greenhouse conditions

Experiments were conducted in a greenhouse located on the campus of the University of Applied Sciences in Weihenstephan, Freising, Germany, (48°24'6"N, 11°43'53"E).

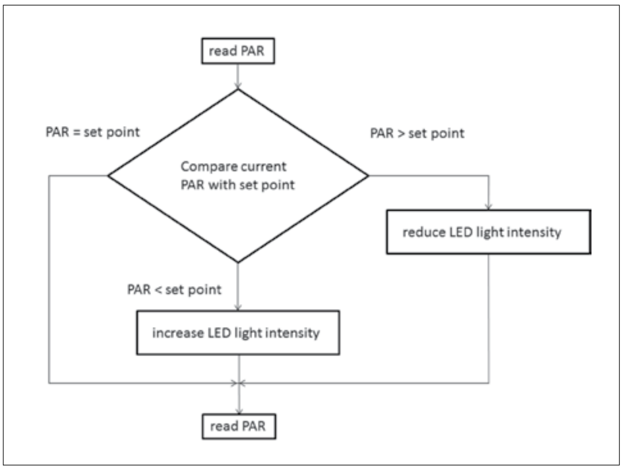

Figure 1. Flow chart of the Visual basic program.

The covering material of the greenhouse was a single layer of glass. Light, temperature and humidity were regulated with a greenhouse computer system (system INT800/KWS, Kriwan, Forchtenberg, Germany). Temperature in the greenhouse was set to 20°C. Solar radiation was measured outside the greenhouse with a luxmeter (Kriwan, Forchtenberg, Germany) and converted to PAR according to the sun light conversion factor of McCree (1972). In the greenhouse PAR was measured constantly with a quantum sensor (LI-190SA, LI-COR Bioscience, Lincoln, NE, USA). The greenhouse was equipped with a red/blue prototype LED fixtures (Osram Opto-Semiconductors, Regensburg, Germany). One LED fixture was connected to the beforehand developed regulation software (further called dynamic LED in the text). The quantum sensor was attached to a pole. During growth the position of the sensor was changed so that it measured the PAR always at the level of the shot tip. The PAR set point was 90 µmol m^{-2} s^{-1}. A second LED was set statically to 90 µmol m^{-2} s^{-1}. The second LED fixture was regulated by the climate computer. The climate computer switched the LED off when the solar PAR exceeded 720 µmol m^{-2} s^{-1} and on when it was below 270 µmol m^{-2} s^{-1}. These values are our standard settings for growth of sunflowers in the greenhouse. This LED is called control LED in the text. Thus, the minimum PAR that was applied was always 90 µmol m^{-2} s^{-1}. If the solar PAR exceeded 90 µmol m^{-2} s^{-1} in the greenhouse, the dynamic LED was off and plants were exposed to solar light only. The control LED, however, was still on, so the light intensity was solar PAR + 90 µmol m^{-2} s^{-1}. Only if the solar PAR exceeded 720 µmol m^{-2} s^{-1}, the control LED was also off.

Previous experiments had shown that it is impossible to grow sunflowers during this period of time without supplementary lighting in Weihenstephan; that is why there was no additional control without lighting. Supplementary light was given for 20 h day^{-1} with a 4-hour night break, which corresponds to a DLI of the control LED of 6.5 mol m^{-2}. The spectrum was set to 50% blue (420–480 nm) and 50% red (620–680 nm), using a spectrometer. Sunflowers were cultivated under these LED lightings until flowering on the 16th of March 2015 (62 days). Data on the DLI in Weihenstephan were obtained from the Deutsche Wetterdienst. Photosynthesis was measured with a phytomonitor on 8 different plants at a time. The leaf chambers of the phytomonitor were equally distributed throughout the canopy. Photosynthesis was measured for 24 h per day in 1-minute steps. The amount of assimilated CO_2 per m^2 was calculated by integration of the photosynthesis rate over time. Energy consumption was measured with an electric meter (Conrad Electronics, Germany). Energy conservation was calculated by subtracting the energy consumptions of the dynamic LEDs from the control LED (given in % of the energy consumption of the control LED).

Stem height and weight, inflorescence parameters, and leaves and diameter and weight of flowers at terminal inflorescence were recorded. Root development was examined visually and graded on a scale from 0 (no growth) to 10 (maximum). ANOVA, Kruskal-Wallis test ($n = 20$) and LOWESS regression were calculated with Minitab (Version 16, London, UK).

Results

In the first experiment, sunflowers were grown in a climate chamber to establish a PAR value that provides an adequate photosynthesis rate. At a PAR > 90 µmol m^{-2} s^{-1}, photosynthesis was greatest at a blue light level of 50% (Figure 2).

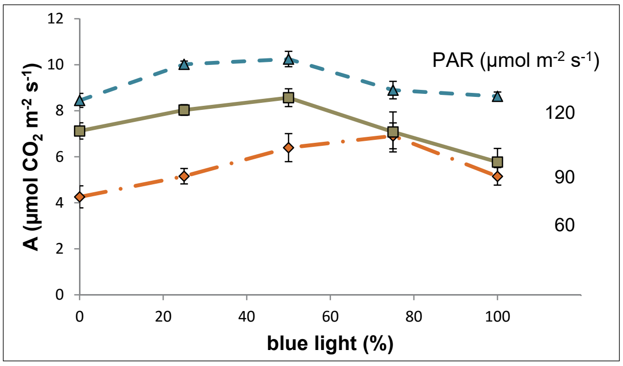

Figure 2. The effect of the light quality on photosynthesis (A) of sunflowers in a climate chamber. Light regimes were blue and red light in various ratios. PAR was 120 (▲), 90 (■) and 60 (♦) µmol m^{-2} s^{-1} and temperature was 20°C. Error bars represent SE (n = 3).

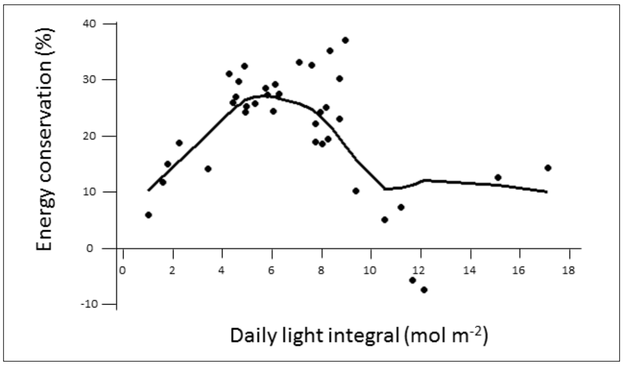

Figure 4. Energy conservation of the dynamic LED at different outdoor DLIs. The period of measurement was January and February 2015. Each dot represents the average energy conservation of one day. Data were smoothed using LOWESS regression.

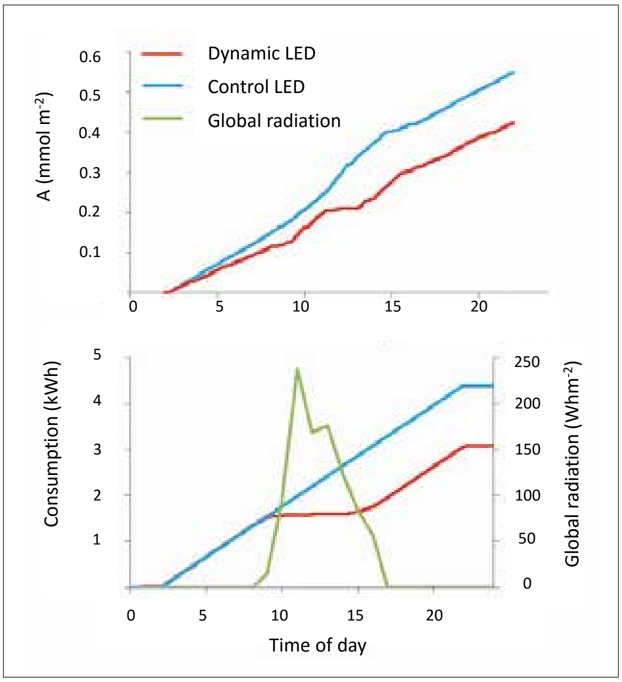

Figure 3. LED energy consumption and corresponding photosynthesis (A) of sunflowers. (A) Integral of photosynthesis and (B) energy consumption of a dynamic (red) and a control LED (blue) during the course of a day. Data were recorded on January the 25th, a day with a DLI of 4.5 mol m^{-2} and a global radiation (green line) < 250 Wh m^{-2}.

At a PAR of 60 µmol m^{-2} s^{-1} photosynthesis was greatest at a ratio of 75% blue and 25% red light. Based on these data, a PAR set point of 90 µmol m^{-2} s^{-1} and a ratio of blue to red light of 1 were chosen for further experiments.

Sunflowers grown in a greenhouse under a dynamic and a control LED using these settings flowered after 62 days. As shown in Figure 3, on one winter day (the 25th of January) the dynamic LED reduced the light intensity as soon as the outdoor global radiation increased. Consequently, also the energy consumption decreased. Concomitantly with the decrease of light intensity the photosynthesis rate decreased. The intensity of the control LED on the other hand remained at a PAR of 90 µmol m^{-2} s^{-1} because the outdoor radiation was still below 720 µmol m^{-2} s^{-1}. Therefore, the integral of photosynthesis was greater under the control LED (Figure 3). These data were consistent throughout the cultivation period, so that on the end of the study the average photosynthesis was significantly lower under the dynamic LED (Table 1). However, there was no significant difference in height, weight, number of leaves, root development or flower weight, number, and diameter. Time to anthesis was also the same.

After 37 days of culturing, the dynamic LED had consumed 116 kWh. During the same period of time the control LED consumed 149 kWh. Thus, on average the dynamic LED consumed 21.1% less energy compared to the control LED. The energy consumption of the dynamic LED varied significantly with the DLI. The energy efficiency was highest when the DLI was between 4 and 9 mol m^{-2} (Figure 4). On two

Table 1. Comparison of sunflower grown under a control and a dynamic LED lighting. Errors represent SD or interquartile ranges (IQR). Significance was tested with ANOVA and Kruskal-Wallis-test (n = 20).

	Control LED	Dynamic LED	p-value
Photosynthesis (µmol m^{-2} s^{-1})	4.4 ± 1.5	4.1 ± 1.7	<0.001
Assimilation CO_2 (mol m^{-2})	1.7 ± 0.5	1.6 ± 0.7	-
Stem height (cm)	46 ± 4	43 ± 3	0.12
Plant fresh weight (g)	153.3 ± 14.3	146.5 ± 8.8	0.27
Flower diameter (cm)	15.3 ± 1.7	15.4 ± 2.3	0.93
Flower weight (g)	27.5 ± 7.1	31.0 ± 9.2	0.40
Number of flower buds	6 ± 1	7 ± 2	0.49
Number of leaves	27 ± 1	27 ± 3	0.84
Days to anthesis	66 ± 1	66 ± 3	0.97
Median root quality (IQR)	7 (0.75)	7 (0.75)	0.75

days the outdoor light intensity exceeded 720 µmol m^{-2} s^{-1} while the quantum sensor in the greenhouse was still in the shade. Consequently, the control LEDs switched off while the dynamic LEDs still emitted light. Therefore, the energy consumption of the dynamic LED was higher than the control LED (Figure 4).

Discussion

This study shows in principle that a dynamic regulation can reduce energy consumption without affecting the quality of ornamental sunflowers. However, the data also show that the average photosynthesis is lower under a dynamic LED. Since the culturing conditions under the two LEDs were the same this data indicates that the reduced of light intensity under the dynamic LED lowers photosynthesis rate. During the course of the study the lower photosynthesis rate resulted in a lower amount of assimilated carbon dioxide (1.6 versus 1.7 mol m^{-2}). Sunflowers grown under the dynamic LED had a lower, but not significantly different fresh weight. In a recent study we reported that a low photosynthesis rate (less than 30% of the control group) significantly lowered fresh weight and compactness (Schwend et al., 2015). In this experiment, the difference in photosynthesis was 7%. Apparently, reducing photosynthesis by 7% is still beyond the threshold at which biomass is affected. Moreover, the lower total light intensity under the dynamic LEDs had no effect on the cultivation time. In this respect sunflowers may be an exception and other species or perhaps even other cultivars will respond differently. For other species it can be crucial to find a different light intensity set point, which guarantees sufficient growth on the one hand side and maximum energy conservation on the other. For instance, most greenhouse lightings deliver less than 4 mol m^{-2} d^{-1} (Faust et al., 2015). However, we chose a set point of 90 µmol m^{-2} s^{-1} (DLI 6.5 mol m^{-2} d^{-1}) based on the experimental data presented in the paper and previous experiences in growing sunflowers with LEDs (Schwend et al., 2015). To find a new set point can be time-consuming and may require several rounds of trial and error.

Moreover, the energy saving potential of this technique depends very much on the outdoor light conditions and the location of the sensor in the greenhouse. Our data suggest that a dynamic lighting has the potential to save energy when the outdoor DLI is below 10 mol m^{-2} d^{-1} and the culture can grow under moderate light conditions.

In this study we focused entirely on the light intensity. Pocock (2015) already thinks one step further and suggests the use of dynamic LEDs to manipulated plant morphology. For instance, it is well known that a low ratio of red to far-red light promotes stem elongation and flower induction through a phytochrome mediated pathway (Smith and Whitelam, 1997). Using a sensor within the canopy that is sensitive to far-red light, this system could be programmed to additionally increase the level of red light in response to high levels of far-red light.

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