Importance of light source position in exposure sequence for optimization of coloration and yield of red winter lettuce

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Winter production of greenhouse crops in northern countries is totally dependent on supplementary lighting. The aim of this study was to investigate the effect of the light source (high-pressure vapor lamps (HPS), light-emitting diodes (LED), or a combination) and their distribution in time on growth and coloration of red winter lettuce (*Lactuca sativa* L. cv. 'Carmoli'). The used energy associated to each of the light treatments was also evaluated. The number of leaves, fresh and dry weight were significantly higher for plants treated only with HPS lights, whereas the red pigmentation was enhanced in plants grown only under LEDs. The lower yield under LEDs was associated with a significantly lower leaf temperature compared to plants grown under HPS lights. One week at the end of the growth period under LEDs was enough to achieve a satisfactory red color, while not compromising plant yield. The energy use efficiency was increased by nearly 50% in the LED-only treatment despite the lower plant yield compared to the HPS-only treatment. These results demonstrate that supplemental light quality can be strategically used by improving the light source position in exposure sequence to enhance the growth and coloration of winter lettuce.

Key words: coloration, hydroponic cultivation, *Lactuca sativa,* light-emitting diode, light source, lighting sequence

Introduction

Growing vegetables in northern regions from mid-September to mid-April is difficult because of the short days and low solar irradiation (Grimstad 1987, Gaudreau et al. 1994, Särkka et al. 2017). Supplemental lighting during the winter months enables all-year cultivation of vegetables. In many countries, there is an increased interest in extensive winter production of vegetables with supplemental light, as this could replace imports from countries at lower latitudes during the winter months. Light conditions, together with other environmental variables (e.g. temperature, humidity, CO_2 concentration) affect the yield and quality of crops, so adjusting environmental growing conditions within the greenhouse is a key to obtaining good yields of high quality products (Gruda 2005).

An important quality parameter in some greenhouse crops like lettuce is leaf color (Gazula et al. 2005). The characteristic red color of lettuce is achieved by ultraviolet-B (UV-B; 280–315 nm) and ultraviolet-A (UV-A; 315–400 nm) radiation that is essential for anthocyanin pigmentation (Voipio and Autio 1995, He et al. 2021). The biological synthesis of anthocyanins is highly dependent on light quality, especially blue (B; 400–500 nm) and ultraviolet (UV; 280–400 nm) radiation through cryptochrome responses (Mancinelli 1985). Lack of UV-B gives a brownish leaf color, which is generally regarded as a low-quality product (Zhang et al. 2019). The level of UV-B radiation varies depending on the season and latitude. In northern regions, the low levels of UV-B radiation emitted by low sun angle and / or a small amount of blue light during low solar irradiation in autumn and winter represent a challenge to the production of high quality red lettuce (Owen and Lopez 2015). In order to effectively grow high quality lettuce during winter, optimization of light conditions is required in the periods of solar radiation shortage (Zhang et al. 2019).

So far, HPS lamps are the most commonly used type of supplemental lighting source in greenhouse production (Pinho et al. 2007). The spectral output of HPS lamps is primarily in the region between 550 nm and 650 nm and is deficient in the UV and blue region (Krizek et al. 1998), so HPS lamps are not ideal for production of high quality red lettuce in winter. Also, for environmental and economic reasons, reduction of energy consumption is becoming more important in greenhouse horticulture. LEDs with their higher electrical efficiency have been proposed as a possible light source for plant production systems and have attracted considerable interest. LEDs present a number of advantages like reduced size, minimum heating and longer theoretical lifespan as compared to HPS lamps. In addition, LEDs allow adjusting the light spectrum and the light intensity to the needs of a specific crop (Bula et al. 1991, Morrow 2008, Mitchell et al. 2012). Combined red (R) + blue (B) LED lights have proven to be an effective light source for producing many plant species, including lettuce, in controlled greenhouse horticulture (Hoenecke et al. 1992, Yorio et al. 2001, Tamulaitis et al. 2005, Bantis et al. 2018). For example, the greenhouse experiment

by Owen and Lopez (2015) showed that the combination of R and B LEDs is more effective than monochromatic R or B in increasing anthocyanin concentration of red-leaf lettuce 'Ruby Sky'. In addition, maximum leaf coloration occurred 7 days earlier and the relative redness was up to 151% higher under R + B LEDs than in plants grown under R or B LEDs alone (Owen and Lopez 2015). However, the high capital cost is still an important aspect delaying the LED technology in horticultural lighting (Särkka et al. 2017). The potential use of different combinations of light sources during the growth period in the greenhouse remains to be studied.

In this study, it was investigated how the growth and coloration of hydroponically grown red winter lettuce was affected by the source of supplementary lighting and their distribution in time, using different exposure times and lighting sequences to HPS or R + B LED lights. The objectives of this study were to determine (1) which exposure times to different light sources and their light type sequence gives the highest yield, while still providing a satisfactory reddening, and (2) which light treatment optimizes energy use.

Material and methods
Growing conditions

A greenhouse experiment with red winter lettuce (*Lactuca sativa* L. cv. 'Carmoli') was carried out in winter 2014/2015 at the experimental greenhouse facilities of the Agricultural University of Iceland at Reykir, Hveragerði (21°12'W, 64°0'N), South Iceland. The experiment was set up in two greenhouse compartments (60 m^2) with different light sources: one of the compartments had HPS top light (10 HPS lamps (Osram, 600 W) and the other had LED top light (10 R + B LEDs (Fiona lighting, 80% R (660 nm) and 20% B (450 nm)). Fixture heights were adjusted to provide a similar photosynthetic photon flux density (PPFD) in the two compartments.

The PPFD at plant canopy height was measured in each compartment by a quantum sensor (LI-190SA; LI-COR, Lincoln, NE) and by a light sensor logger (LI-250A; LI-COR, Lincoln, NE). PPFD amounted in average 165 µmol m^{-2} s^{-1} for the HPS compartment and 164 µmol m^{-2} s^{-1} for the LED compartment, respectively. White plastic on all surrounding walls helped to get a higher light level at the edges of the growing area. As the experiment was conducted during the darkest time of the year, the solar irradiation stayed at around 1 kWh m^{-2} week^{-1} during the whole experiment. This was equivalent to no solar irradiation coming into the greenhouse, thus the PPFD was constant in the greenhouse during the whole growth period.

Seeds of red winter lettuce were sown on 11 November 2014 in pots (diameter: 6 cm) containing peat substrate (pH 6.0, B2S, Kekkilä Professional, Vantaa, Finland). Seedlings were produced under optimal conditions (temperature of 19 °C during day / 15 °C at night, light intensity of 200 µmol m^{-2} s^{-1} with supplemental HPS lighting from 0500 h to 2300 h). On 26th of November, the most equal sized two-week old seedlings (in total 3344 seedlings) at the 2-leaf stage were selected and transferred to nutrient film technique (NFT) channels (width: 7 cm, slope: 1 cm m^{-1}, 70 cm height from the ground, total number of channels: 176) in the two greenhouse compartments and grown hydroponically for four weeks, which is the normal growth period for lettuce. Each NFT channel had a length of 4.06 m and was equipped with 19 pots, with a distance of 21 cm between pots.

The plants growing in the NFT channels were exposed to an 18-h photoperiod (from 0500 h to 2300 h) of eight different light treatments. Each light treatment consisted of 16 NFT channels. Some channels were exposed during the whole growth period to HPS light only, while other channels received only LEDs, while the other channels were moved weekly between the two greenhouse compartments, to achieve different combinations in the timing and duration of exposure to different light sources:

1. 4 weeks under HPS light (HPS, HPS, HPS, HPS)
2. 3 weeks under HPS light and 1 week under LED light (HPS, HPS, HPS, LED)
3. 2 weeks under HPS light and 2 weeks under LED light (HPS, HPS, LED, LED)
4. 1 week under HPS light and 3 weeks under LED light (HPS, LED, LED, LED)
5. 1 week under LED light and 3 weeks under HPS light (LED, HPS, HPS, HPS)
6. 2 weeks under LED light and 2 weeks under HPS light (LED, LED, HPS, HPS)
7. 3 weeks under LED light and 1 week under HPS light (LED, LED, LED, HPS)
8. 4 weeks under LED light (LED, LED, LED, LED)

The density of the plants followed general recommendations for greenhouse-grown lettuce, and the distance between channels was adjusted weekly according to the growth of the lettuce, from no space (first week) between channels to 5 cm (second week), 10 cm (third week), and 15 cm (fourth week), giving a plant density of 68, 40, 28, 22 plants m^{-2}, respectively. With decreasing plant density was the number of channels in each light treatment reduced due to the given size of the greenhouse compartments.

The greenhouse air temperature set points were 19 °C / 15 °C (day / night). The greenhouse compartments provided computer-controlled microclimate conditions. Growing conditions (air temperature, floor temperature, CO_2 concentration) were similar between the greenhouse compartments (Table 1). However, humidity was higher in the HPS compartment.

Table 1. Microclimate conditions, leaf temperature of red winter lettuce (*Lactuca sativa* 'Carmoli') and temperature of the substrate in the greenhouse compartments with either HPS or LED light.

Growing conditions	HPS Compartment	LED Compartment
Air temperature (°C)	18.3 a [z]	18.4 a
Floor temperature (°C)	35.3 a	32.9 a
CO_2 (ppm)	818 a	828 a
Humidity (%)	56.7 a	52.7 b
Temperature in substrate (°C)	18.9 a	17.5 b
Leaf temperature (°C)	16.4 a	13.1 b

[z] The differences between the greenhouse compartments for each variable are based on paired t test. Different small case letters indicate significant differences between means at the p = 0.05 level.

Lettuce plants received standard fertilizer containing (ppm) 175 N – 40 P – 290 K – 130 Ca – 34 Mg – 47 S – 2.20 Fe – 0.60 Mn – 0.35 B – 0.30 Zn – 0.15 Cu – 0.06 Mo. The pH and electrical conductivity (EC) values of the watering system were monitored during the plant growth and adjusted to an EC of 1.6 mS cm^{-1} and adjusted to a pH of 5.2–5.5 and a pH of 5.5–6.0 in the applied and runoff water, respectively.

Sampling and measurements

The NFT channels with the different light treatments were distributed in four repetitions in a randomized complete block design.

Substrate temperature was measured in the middle and at the end of the growth period in 1–2 cm depth by a portable thermometer (testo 926, Testo SE & Co. KGaA, Titisee-Neustadt, Germany) and leaf temperature by a portable infrared contact thermometer (BEAM infrared thermometer, TFA Dostmann GmbH & Co. KG, Wertheim-Reicholzheim, Germany) at one channel of each repetition in each greenhouse compartment.

Plants were harvested after four weeks by cutting the lettuce head at the hypocotyl. Ten plants were randomly selected from each NFT channel to assess plant growth and leaf coloration. Plant measurements thus represent individual measurements of 40 plants (four repetitions consisting of ten individual plants each) for each light treatment. The number of leaves at least 2 cm in length was counted. The fresh weight (FW) of each plant was measured and after drying in an oven for a minimum of 24 h at 105 °C until constant weight the dry weight (DW) was measured.

The color of leaves was determined by a color palette using the red-green-blue (RGB) color model (Waskale and Bhong 2017), which was previously correlated with the content of anthocyanins (Gazula et al. 2007). In this human sensory evaluation, an integer number is given to a leaf based on its color, with higher numbers representing a higher percentage of red (e.g. number 9 represents 120 green and 80 red, number 10 represents 110 green and 90 red, number 11 represents 100 green and 100 red and so on). A color number of more than 11 was evaluated as satisfactory color / good red pigmentation. The measured color was consisting of the average color of one representative leaf per plant. As for the other plant measurements, also here were 40 plants at each light treatment measured.

To assess energy use in the different light treatments, the daily energy use (kWh) by supplemental lighting was measured in each greenhouse compartment by dataloggers. The energy use of each light treatment was then calculated based on the time that each plant was growing in each compartment. Since growth of plants differed in the two compartments, a more useful indicator for economic evaluation is the energy use efficiency, calculated as the FW of the plant divided by the amount of energy needed to produce it (expressed as g per kWh).

Statistical analysis

The experiment used a randomized complete block design with four repetitions. There were ten samples (individual plants) per repetition per light treatment. Statistical analysis was carried out using SAS (SAS 9.4, SAS Institute, Cary, NC). The effect of different compartments was evaluated using paired t test. For the effect of light treatments was the mixed model procedure (PROC MIXED) used for analysis of variance. The NFT channels were treated as random effects. Differences among least squares treatment means were determined using pairwise t tests implemented by the PDIFF option at the significance level α = 0.05. Correlation analyses were calculated on treatment means using the SAS procedure "prog corr". Reported significance levels were $p < 0.05$ (*), $p < 0.01$ (**) and $p < 0.001$ (***).

Results

Substrate and leaf temperature

The average substrate temperature was more than 1 °C higher under HPS lights (Table 1). Also, the average leaf temperature was 3 °C higher for lettuce plants growing in the HPS compartment compared to the LED compartment (Pr > F: 0.0001).

Plant growth

The number of leaves was correlated with the FW (r^2 = 0.96***) and DW (r^2 = 0.72**) of 320 lettuce plants: a higher leaf number involved a higher yield. Plants showed distinct growth responses to different light treatments. Leaf number, FW and DW of the plants were the greatest when grown under HPS light only, and lowest under LEDs only (Fig. 1). The FW was 28% and the DW 22% lower when grown under LEDs only compared to HPS lights only. Plants that received only HPS light developed significantly more leaves (19 leaves head^{-1}) than plants that were grown under LEDs only (14 leaves head^{-1}) (Fig. 1A). Plants that received LED light for one, two or three weeks tended to have a reduced number of leaves as compared to plants under HPS, depending on the duration of LEDs used (r^2 = 0.90***). The order of exposure to LED or HPS light did not seem to matter much, as there were no differences in the number of leaves between treatments e.g. "HPS, HPS, HPS, LED" and "LED, HPS, HPS, HPS", or "HPS, HPS, LED, LED" and "LED, LED, HPS, HPS".

The highest FW (164 g head^{-1}) was found for the lettuce plants grown the whole growth period under HPS lights. A significantly lower yield (118 g head^{-1}) was obtained for the plants grown the whole period under LEDs (Fig. 1B), while the other light treatments presented intermediate values of FW that were significantly different to both the only HPS lights treatment as well as to the only LED treatment. The final FW was dependent on sequence and duration (r^2 = 0.93***) of supplemental lighting with LEDs: Plants that received LEDs at the beginning of the growth period for three weeks or at the end of the growth period for three weeks, had a significantly lower FW compared to plants that received at the beginning of the growth period for one week LEDs or at the end of the growth period for one or two weeks LEDs (Fig. 1B). Similarly, higher DW was measured with the application of HPS lights only (23 g head^{-1}) in comparison to LEDs only (18 g head^{-1}) (Fig. 1C). Plants that received LEDs at the beginning of the growth period for one, two or three weeks or at the end of the growth period for three weeks, had a significantly lower DW compared to plants that received the whole time only HPS light, the first three or the first two weeks HPS light, whereas plants that received LEDs at the beginning of the growth period for one, two or three weeks showed no yield difference to plants that were grown the whole time under LEDs (r^2 = 0.56*). Differences in the order of light application in the combined light treatments were obvious: Treatments "HPS, HPS, HPS, LED" had a significantly higher DW than "LED, HPS, HPS, HPS", "HPS, HPS, LED, LED" had a significantly higher DW than "LED, LED, HPS, HPS" and "HPS, LED, LED, LED" had a significantly higher DW than "LED, LED, LED, HPS".
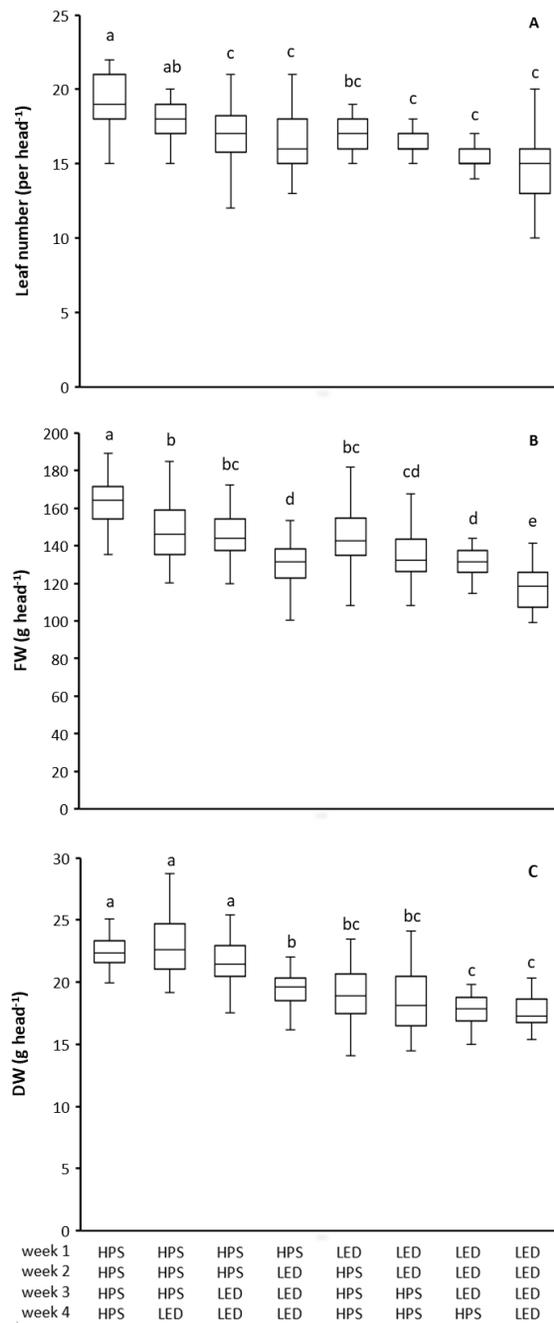
Fig. 1. Leaf number (A, Leaf number includes leaves ≥ 2 cm), fresh weight (FW, B) and dry weight (DW, C) of red winter lettuce 'Carmoli' after four weeks growth period under different light treatments. Lettuce plants received either the whole growth period HPS or LED light, or different number of weeks HPS and LED light. Plant measurements represent individual measurements of 40 plants for each light treatment (four repetitions consisting of ten individual plants each). Differences between the light treatments are based on pairwise t test, and letters indicate significant differences at the p = 0.05 level.

Coloration of lettuce

The light source affected the reddening of the lettuce plants: Four weeks after planting into the NFT channels had lettuce a more intense red pigmentation (a higher color number in the RGB model) when the plants were exposed to LED for one week or longer at the end of the growth period (Fig. 2). The coloration of plants that were exposed to LEDs for one week at the end of the growth period was as intense red as for plants that received the whole growth period only LED lights. The color number was more than 11 and evaluated as a good red pigmentation. In contrast, when lettuce plants were exposed to LEDs at the beginning of the growth period and to HPS lamps after that, they had a significantly lower color intensity.
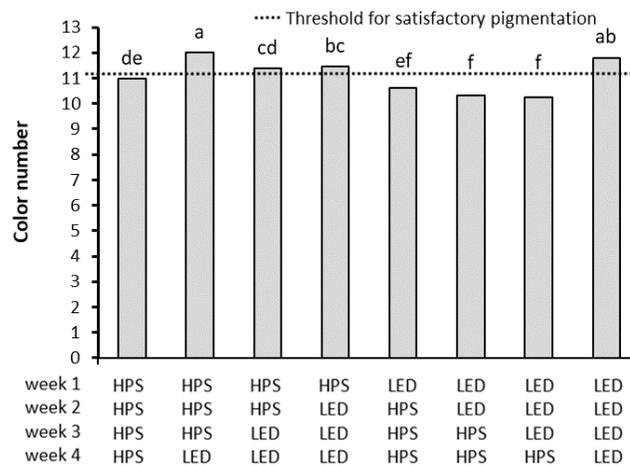
Fig. 2. Coloring (RGB color model; number 9 represents 120 green and 80 red, number 10 represents 110 green and 90 red, number 11 represents 100 green and 100 red and so on) of red winter lettuce 'Carmoli' after four weeks growth period under different light treatments. Lettuce plants received either the whole growth period HPS or LED light, or different number of weeks HPS and LED light. Mean values based on individual measurements of 40 plants for each light treatment (four repetitions consisting of ten individual plants each). Differences between light treatments are based on pairwise t test and different letters indicate statistically significant differences between means at the p = 0.05 level.

Energy use efficiency

The energy use per light treatment ranged between 4230 kWh (151 kWh day^{-1} × 28 days) in the treatment with only HPS lights, and 2066 kWh (74 kWh day^{-1} × 28 days) in the treatment with only LEDs. Therefore, the energy costs of growing lettuce could be reduced by 50% with the use of LEDs. The use of kWh was correlated with a high FW (r^2 = 0.93***), but energy use efficiency, FW per used kWh, increased with a longer use of LEDs (r^2 = 0.92***). When lettuce plants were only exposed to LEDs, significantly more yield was reached per kWh compared to plants exposed only to HPS lights (Fig. 3). The utilization of kWh's was also significantly higher when HPS lights were used only for one week or two weeks at the beginning of the growth period or for one week at the end of the growth period compared to the only use of HPS lights. However, the use of LEDs for one week or two weeks at the beginning of the growth period or for one week at the end of the growth period was not statistically different from the use of HPS lights only.
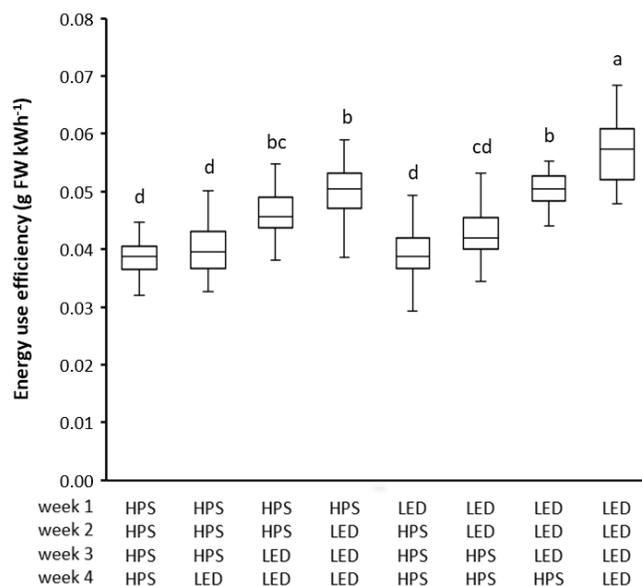

Fig. 3. Energy use efficiency of red winter lettuce 'Carmoli' after four weeks growth period under different light treatments. Lettuce plants received either the whole growth period HPS or LED light, or different number of weeks HPS and LED light. Plant measurements represent individual measurements of 40 plants for each light treatment (four repetitions consisting of ten individual plants each). Differences between light treatments are based on pairwise t test and different letters indicate significant differences between means at the p = 0.05 level.

Discussion

Plant yield and quality are the result of interactions of various environmental factors under which plants are grown. The present study examined the effect of different light sources and their position in exposure sequence on the yield and quality of red winter lettuce plants grown under, otherwise, the same environmental conditions. Irradiation with R + B LED lights decreased growth and yield of lettuce plants. After four weeks with different light treatments, the FW and DW were highest for lettuce plants under HPS lights and about 28% and 22% lower for plants under LEDs. This concurs with the results of Hernández and Kubota (2015) and Treder et al. (2016) where cucumber seedlings grown with HPS lights were heavier than seedlings exposed to LEDs. However, different crops may respond differently to light sources (Treder et al. 2016). Hernández and Kubota (2014) reported similar growth of tomato plants under R LED lights and HPS lights. Similarly, the growth and biomass of different varieties of crops can be influenced by the quality of supplemental lighting: Brazaitytė et al. (2006) did not observe any growth differences under HPS and R + B LEDs among lettuce 'Grand Rapids', and neither did Zhang et al. (2019) and Hernandez et al. (2020) for different lettuce cultivars. Also, Martineau et al. (2012) measured a similar shoot biomass of Boston lettuce under HPS and LEDs during a 18-h photoperiod, even though the average total light irradiance amounted to 72.3 µmol m^{-2} s^{-1} for HPS and 35.8 µmol m^{-2} s^{-1} for LED, respectively. Thus, potentially they could have gotten higher yield for LED if they had standardized the amount of PPFD µmol m^{-2} s^{-1}. Other studies are even showing a higher yield with LEDs than with HPS: e.g., Pinho et al. (2007) reported that lettuce 'Frillice' grown under R + B LED in the greenhouse had a 53% greater FW compared with that under HPS, both at a PPFD of 120–140 µmol m^{-2} s^{-1}. Similarly, the yield of lamb's lettuce under monochromatic R or R + B LEDs increased by 18–26% or 18–41%, respectively, in two consecutive winters compared with that under HPS, both at a PPFD of 200 µmol m^{-2} s^{-1} (Wojciechowska et al. 2015). Therefore, different crops or even varieties respond differently to light intensity and quality. The sensitivity of lettuce to the quality of supplemental lighting seems to be variety-specific, and more studies are merited.

An important parameter in the quality of red winter lettuce is its characteristic red pigmentation. This study showed that the red color of lettuce was triggered by the use of R + B LED lights. After one week or more weeks' exposure to LEDs at the end of the growth period, lettuce plants showed higher levels of coloration compared to plants that received HPS lights and had an insufficient red color. This was likely due to a higher content of anthocyanin induced by UV-radiation that enhances the red color in lettuce and improves the external quality and marketability of the product (Rodriguez et al. 2014). As the RGB model was correlated to the content of anthocyanin (Gazula et al. 2007) this color model is suitable for making statements regarding red pigmentation and content of anthocyanin. This explains why the treatment "HPS, HPS, HPS, LED" and the LED-only treatment had the highest color number as this was correlated to the highest content of anthocyanin. The presented findings are in agreement with the report of Samuolienė et al. (2012) who investigated lettuce 'Multired 4' grown under HPS lamps providing 170 µmol m^{-2} s^{-1} with the addition of blue (455 or 470 nm) or green (505 or 530 nm) LEDs delivering 30 µmol m^{-2} s^{-1} for 16-h. The authors concluded that supplemental lighting with blue light enhanced anthocyanin content. Indeed, De Keyser et al. (2019) reported that the use of R + B LEDs resulted in a more intense pigmentation due to increased anthocyanin synthesis in leaves and bracts of pot plants at the end of the production cycle. Also, Owen and Lopez (2015) reported more red pigmentation of different varieties of lettuce ('Cherokee', 'Magenta', 'Ruby Sky', and 'Vulcan') with LED (100 µmol m^{-2} s^{-1} delivered from 100:0, 0:100, and 50:50 R:B light) in comparison to HPS lights at a lower light intensity (70 µmol m^{-2} s^{-1}). In that study plants were grown the first five weeks under HPS lights only, but after that exposed to different light sources. However, as light quality affected the content of anthocyanins, the exposure sequence contributed significantly to coloration. The light source at the end of the growth period determined whether or not the coloration of lettuce was rated satisfactory. Similarly, Stutte et al. (2009) reported that the pigmentation of red leaf lettuce did not persist to harvest unless there was blue light in the spectra. Hence, UV-B exclusion to red oak leaf lettuce led to a decline in anthocyanin content (Behn et al. 2011). Additionally, the authors found that a short application of UV-B for two days at the end of the growth period caused a much stronger response in younger (inner) leaves than in older (outer) leaves compared to constant UV-B application for 23 days. Owen and Lopez (2015) also reported that a minimum of five days exposure to LED lights at the end of the growth period was enough to enhance red pigmentation. This is in accordance with the present findings, where induction with LEDs for more than one week gave no redder color compared to only one week under LEDs. Therefore, a relatively short time (one week) under R + B LEDs seems to be enough to induce anthocyanin synthesis and red coloring. With that, the quality of red lettuce could be improved without a significant decrease in FW or DW. Therefore, R + B light provided by LEDs can be successfully used to promote anthocyanin accumulation and leaf color of lettuce.

Substrate and leaf temperature were about 1 °C and 3 °C lower, respectively in the LED compartment than in the HPS compartment. This is probably a reason for the delayed growth of lettuce at lower temperature as temperature is known to affect leaf initiation and growth (Hernández and Kubota 2015). For example, a higher FW of cucumbers under HPS lights has been attributed to the higher leaf temperature when compared to plants grown under LEDs, as HPS lamps emit more heat (Treder et al. 2016). Indeed, a higher substrate and leaf temperature was associated with bigger plants in the presented study (significant correlations between substrate temperature and FW (r^2 = 0.85**) or DW (r^2 = 0.81**) and between leaf temperature and FW (r^2 = 0.65*) or DW (r^2 = 0.78**)). It can therefore be expected that increasing the leaf and substrate temperature in the LED compartment to the same value as in the HPS compartment, could induce a faster growth of plants and with that a higher crop yield. As environmental factors (light quantity, quality, and duration and temperature) are also influencing the production of anthocyanin (Rabino and Mancinelli 1986), a higher temperature might also influence red coloration.

High energy savings of about 50% were achieved with LEDs compared to HPS lights, meaning by using LEDs, kWh were transferred better into yield. Pinho et al. (2013) measured 40% energy savings and Hernandez et al. (2020) reported even more than 60% energy savings with LEDs compared to HPS lights, however, with no yield differences for lettuce plants between light sources. Martineau et al. (2012) reported energy savings of at least 33.8% for the production of lettuce with LEDs, but used a lower light intensity (35.8 µmol m^{-2} s^{-1}) compared to HPS lights (72.3 µmol m^{-2} s^{-1}). When plants were exposed to HPS lights in the beginning of the growth period and after that to one, two or three weeks LED lights, in addition to a better red coloration and energy use efficiency, energy savings were achieved that amounted to more than 10%, 25% or nearly 40%, respectively compared to the only use of HPS lights.

A combination of supplemental lighting with HPS and R + B LEDs would simultaneously optimize yield and pigmentation of red winter lettuce, while at the same time saving electricity when compared to the use of only HPS lights. Olle and Viršilė (2013) came to the same conclusion, that a hybrid lighting system that combines some of the features of LEDs with conventional HPS fixtures could be an economically efficient option.

Conclusions

In conclusion, the results indicate that growing lettuce under HPS lights guarantees a stable growth of lettuce plants after transplanting, however with a non-satisfactory reddening. In contrast, lettuce plants showed a clear response by increasing red color when plants were exposed to LED lighting at the end of the growth period. However, with increasing duration under LED lights growth, FW and DW was reduced, whereas the electricity consumption was better transferred into yield. Therefore, it is recommended to use HPS lamps with a supplement of R + B LEDs for one week at the end of the growth period. However, as discussed, further experiments with a higher temperature under LEDs as well as a combination of lighting with HPS lights and LEDs together need to be tested before final conclusions and recommendations can be made.

Acknowledgements

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