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Evaluation of Lettuce Growth under Multi-spectral-component Supplemental Solid State Lighting in Greenhouse Environment

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Abstract – *Light-emitting diodes (LEDs) have been useful in evaluating plants's physiologic and growth responses to radiation quality and quantity. In the great majority of these studies, growth rooms (phytotrons) have been used in order to avoid the influence of external factors such as the daylight radiation. The main objective of this study was to evaluate the growth performance of two LED-based supplemental lighting treatments (LED1, LED2) on lettuce (Lactuca sativa var. crispa L., 'Frillice') cultivation in real glass greenhouse conditions. Control plants were grown under conventional high-pressure sodium (HPS) lamps. In LED1 treatment red-orange (RO) and blue LEDs with peak wavelength emissions at 630nm and 460nm, respectively were used while in LED2 an additional yellow component at 594nm was also included. The results had indicated that lettuce growth parameters can be improved using supplemental spectral-tailored LED lighting. RO LEDs were also effective in promoting biomass accumulation and the addition of a small percentage of yellow photons may further enhance this aspect and increase the number of leaves per plant. The results have also suggested a relation between the amount of blue photons and yellow-green photons in lettuce growth.*

***Keywords**: Light-emitting diodes, supplemental lighting, greenhouse, lettuce, energy efficiency*

I. Introduction

Similarly to discovering of spectral influence of light on plant development, also the electroluminescent effect has been known for more than a century [1]-[2]. However the commercial mass production of light-emitting diodes (LEDs) has only begun in early sixties. Nowadays LEDs have become a promising light source with potential to be used in large variety of applications including horticultural lighting. Solid state lighting in contrast to broadband light sources commonly used in horticulture, can be fabricated and controlled in order to produce the most appropriated spectrum for healthy growth of the crop [3]. Several studies have shown the viability of using LEDs in controlling plant growth development [4]-[9]. Most of these studies have been carried out in controlled environment growth chambers or rooms, also called phytotrons. Growing plants in phytotrons is useful for experimental purposes due to the relatively easy control of the main environment growth parameters, such as temperature, humidity, carbon dioxide (CO_2) concentration and photosynthetic photon flux (PPF) daily integral. All these factors can be controlled independently of external influences. Phytotrons are also useful in the evaluation and optimization of specific artificial lighting systems, treatments or strategies intended to benefit crop quality and its growth development.

Unfortunately, for commercial year-round crop production, the use of phytotrons is not economically viable due to the high initial installation and running costs [10]-[11]. Moreover, well-succeeded lighting strategies in phytotrons do not necessarily produce the same results in greenhouse conditions, especially when daylight is also involved. Spectrum, quantity and periodicity variations of daylight are likely to trigger important physiological responses which are likely to influence the growth, nutritional quality and hormone balance of crops. Therefore predicting the effects of LED-based supplemental lighting (SL) in greenhouse environment based on phytotron trials may not always provide conclusive answers. This is due in large part to the variety of known and also not yet known photopigments and their interrelations and interdependences. Some of these interactions and interdependences are still under investigation and in some aspects their working mechanisms still are not well understood [1], [12].

At northern latitudes due to the reduced daylight availability during winter, the utilization of SL allows year-round commercial crop production [13]. High-pressure sodium (HPS) lamp is the main light source used by owners of glass and double plastic greenhouses. With SL is possible to influence important processes such as photosynthesis, growth, photomorphogenesis, floral evocation, flower development, yield and quality [14]. In year-round commercial vegetable crop

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production in greenhouses the electrical energy costs accounts for approximately 1/3 of the total overhead costs [15]. Therefore high-efficiency lighting technologies are desirable for year-round horticulture industry. Combining high photon flux, electrical efficiency, spectral and emission control in one luminaire is likely to be a reality in the future due to the fast development of LEDs. Besides improving the crop quality such luminaires could also contribute to reduce the global energy consumption, reduce CO_2 emissions and slow down the undeniable global warming by improving the production efficiency.

Until now there have not been sufficient reports of studies using LEDs as SL in real greenhouse conditions for lettuce growth. This study contributes to address this lack of knowledge by comparing the growth performance of lettuce plants under two different multi-spectral-component supplemental LED lighting treatments in real greenhouse conditions with conventional high-pressure sodium lamp (HPS) lighting. Additionally the study also concludes about the viability of using red-orange LEDs in substitution of more expensive and unreliable aluminum gallium arsenide (AlGaAs) red LEDs which emit closer to peak absorption of chlorophyll-a at 660nm. The effects of spectral quality resulting from the combination of aluminum gallium indium phosphide (AlInGaP) and aluminum indium gallium nitride (AlInGaN) modern LED types as SL is evaluated. Namely, the effects of combining red-orange radiation with blue alone or with blue and yellow were investigated.

The study builds up on results gather from a growth trial carried out in southern of Finland (Piikkiö, 60°23'N, 22°33E) during winter season between January 17th and March 1st 2005. Lettuce plants grown under the LED lighting were compared with control plants exposed HPS lighting. The biometric characteristics, growth rates and light utilization efficiencies were used to evaluate the growth performance of the LED luminaries and its viability as SL.

II. Material and Methods

Lettuce *(Lactuca sativa* var. crispa L., 'Frillice') plants were grown in peat substrate with a 20h/4h (day/night) photoperiod and an average ambient temperature of 18/15°C (day/night). The average humidity level and CO_2 concentration was in average 60% and 700 ppm, respectively. The referred ambient parameters of the room were maintained throughout the experiment duration.

The seeds were planted in small pots under black-white plastics from were germinated after 3 days. After germination, lighting treatments were initiated. Each treatment comprises a 60x60cm illuminated growth area. After the 2nd week the plants were transplanted into 12-cm diameter pots. Plants measurements were done weekly gradually reducing the number of plants involved. The experiment was conducted in one room of a twin-wall acrylic type greenhouse with a roof of glass.

The experiment set-up was composed by three lighting systems (HPS, LED1 and LED2) with different spectral qualities and similar PPF at plant canopy. In HPS the control plants were grown under two 70-W high-pressure sodium (HPS) lamps (VIALOX® NAV® (SON)-T, *Osram GmbH*, Germany). In LED1 the illumination was provided by a combination of red-orange and blue LEDs in the same luminaire. In LED2 together with red-orange and blue, the luminaire included also a third group of LEDs emitting in the yellow region. The red-orange component was provided by AlInGaP LEDs (DRAGONtape™, OS-DT6-A1, *Osram Opto Semiconductors GmbH*, Germany) with peak emission at 630nm. The blue component was delivered by InGaN LEDs (DRAGONtape™, OS-DT6-B1, *Osram Opto Semiconductors GmbH*, Germany) with peak emission at 460nm. The yellow component was used only on LED2 and was delivered by AlInGaP LEDs (DRAGONtape™, OS-DT6-Y1, *Osram Opto Semiconductors GmbH*, Germany) having a peak emission at 594nm.

The average PPF on the growth area due to supplemental lighting was approximately 90µmolm^{-2}s^{-1} for HPS and LED1 while for LED2 was 75µmolm^{-2}s^{-1}. In LED1 the red-orange basal component was 80% of the total PPF. For LED2 the amount of red-orange component was reduced to 44% while a third component in yellow representing 17% of the total PPF was added. The short-wavelength component in blue region was similar for both LED treatments. The relative amount of blue photons was 20% and 24% for LED1 and LED2, respectively (see Fig. 1).

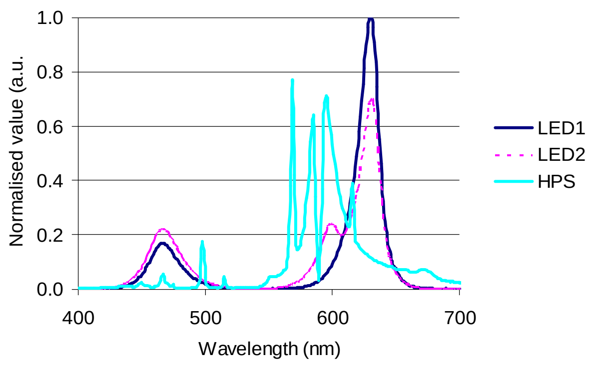

Fig. 1. Relative PPF spectral distribution balance of LED1, LED2 and HPS lighting treatments at the centre of the growth areas

Due to the differences between the spatial photon distribution characteristic and the total average PPF level on the growth area, plants had to be grouped according to 4 PPF levels (60-80, 80-100, 100-120 and 120-140µmolm^{-2}s^{-1}). In this way plants grown under the same PPF level could be averaged and compared. The PPF at plant canopy level was measured with a LI-

191SA line quantum sensor (LI-COR, Lincoln, NE, USA).For spectral radiation measurements a high-resolution portable spectrometer (HR4000, *Ocean Optics Inc.*, USA) was used. The leaf area was measured with leaf area meter (LI-3100, *LI-COR, Lincoln*, Nebraska, USA).

In order to reduce the differences on the amount of daylight contribution and lateral lighting interferences, high-reflective white plastic curtains were placed around each lighting system. The exterior black-painted side of the curtain prevented light interference between the treatments. The interior of the curtains were of a high-reflective white colour intended to redirect the daylight coming from above to growth area reducing the shadowing effects and increasing uniformity.

III. Results and Discussion

III.1. Lettuce Growth and Development

After the first week of growth, young lettuce plants submitted to LED1 and LED2 lighting treatments had the shortest hypocotyls elongation, which was in average slightly below 15mm. This value has represented 50% reduction of hypocotyls elongation in average in relation to control plants. Increasing the PPF level has also contributed to reduce the hypocotyls elongation. The plants grown under higher PPF levels have shown smaller hypocotyls elongation. The hypocotyls length difference between young lettuce plants grown under the LEDs and HPS light has shown the tendency of increasing at higher PPF levels (see Fig. 2). The smaller hypocotyls sizes and leaves lengths of plants grown in LED1 and LED2 have resulted in a more compact foliages and improved morphology in comparison with control plants.

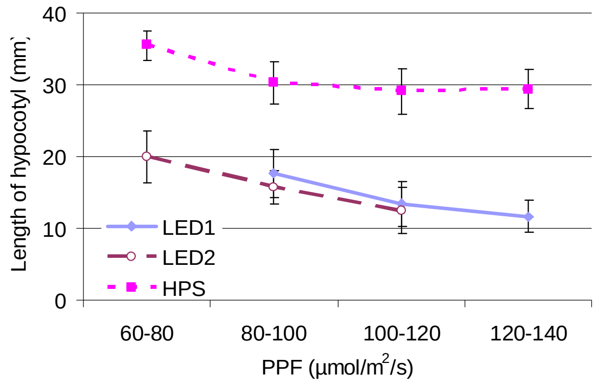

Fig. 2. Hypocotyl elongation at different supplemental PPF levels at week 1

Interesting for commercialization point-of-view of lettuce was the highest number of leaves obtained due to LED2 at 100-120µmolm^{-2}s^{-1} PPF. This result agrees with previous studies which have shown that yellow light radiation by broadband filtered light sources peaking at 570 and 590nm increased significantly the number of lettuce leaves [16]. The number of leaves per plant on LED2 was consistently higher along all growth period in comparison to LED1 and control plants (see Fig. 3). At week 6 LED2 grown plants had in average 42 leaves followed by LED1 with 37 and control plants with 35 based on measurement of 3 plants.

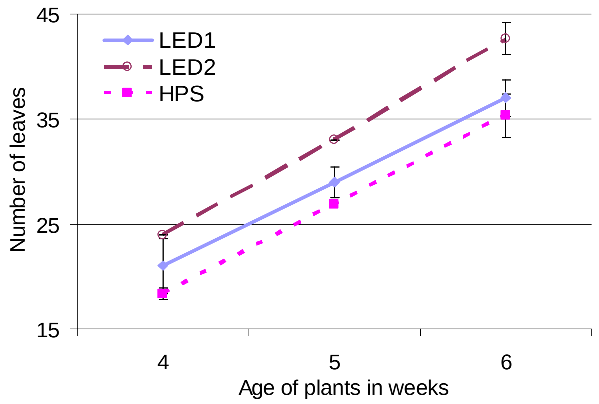

Fig. 3. Evolution of leaf number between week 4 and week 6 for plant grown under 100-120µmolm^{-2}s^{-1} supplemental PPF

The leaf area of plants grown in LED1 and LED2 lighting treatments was more sensitive to PPF increase than HPS grown plants. The results have shown that for the LED1 treatment the plants grown under higher PPF had 40% higher leaf area expansion (LAE) rate between week 2 and week 6. For the same time period and PPF increase, the increment LAE rate for control plants was approximately 7%.

At the end of growth trial the fresh weigh (FW) was approximately 53% higher for LED1 plants than for the control plants grown under a PPF of 120-140µmolm^{-2}s^{-1} (see Fig. 4).

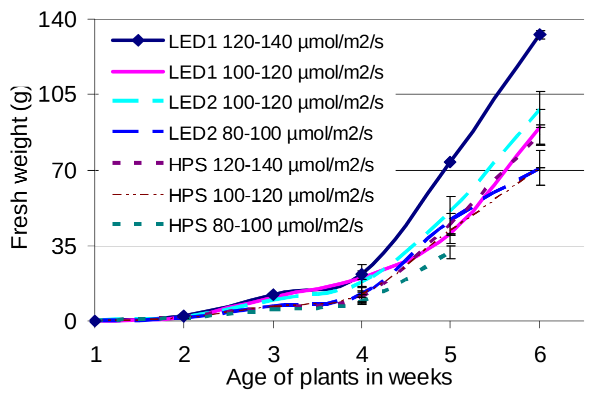

Fig. 4. Evolution of fresh weight between week 1 and week 6 at different supplemental PPF levels

At lower PPF (100-120µmolm^{-2}s^{-1}) the tendency was the same but the percentage of increase was smaller.

LED2 treatment was the most effective in accumulation of FW at the end of week 6. The percentage of dry weight (DW) in relation to FW was highest for the control plants followed by the LED1 and LED2.

The opposite tendency was observed with the fresh weight accumulation rate (FWAR) between week 2 and week 6 with 100-120µmolm^{-2}s^{-1} PPF. The highest FWAR was for the LED2 followed by LED 1 and HPS. Until week 4 the FWAR on LED2 has been similar to the LED1 but between week 4 and week 6 there was a slight increase on FWAR, which explains the final FW results (see Fig. 5). Similarly to the leaf area, the FW of plants grown in LED1 and LED2 treatments was more sensitive to PPF increase than HPS grown plants. It was verified that for LED1 grown plants, the increase in the PPF has resulted in higher FW accumulation in comparison with control plants.

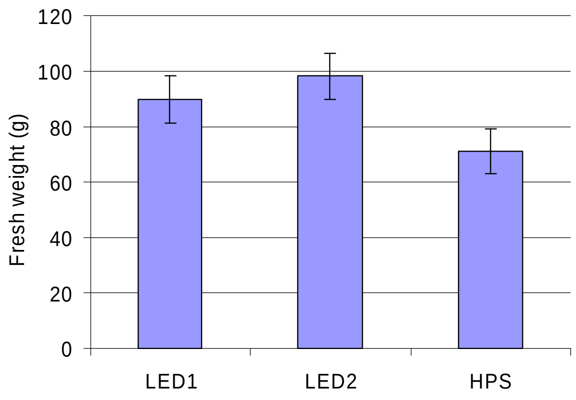

Fig. 5. Averaged fresh weight at week for plants grown under 100-120µmolm^{-2}s^{-1} supplemental PPF

III.2. Influencing Factors

Environmental parameters are important factors in comparative plant growth evaluation trials. During the growth trial the ambient temperature and the total daily PPF integral were two important environmental factors, which therefore are here further discussed.

In order to simplify and clarify the analysis of the results obtained, the daylight contribution to the total daily PPF integral should be approximately the same in all treatments. However due to the different form factor, shape, photosynthetic photon flux and spatial pattern distribution characteristics of the luminaires used, this was not totally achieved. The unconventional optical, electrical and thermal characteristics of LEDs make the obtaining of a LED luminaire with exact same optical characteristics of conventional HPS luminaires a non trivial process. The smaller form factor of HPS luminaires resulted in lower shadowing effects on control plants than on LED grown plants. This has naturally increased the daily PPF integral due to daylight contribution on HPS treatment benefiting the growth of control plants. Nevertheless and on spite of this, the overall plant measurement results have been always favorable to the LED lighting treatments.

The quantity and quality of daylight radiation contribution to the total PPF has varied accordingly to the weather conditions. Also the availability of daylight has increased fast along the growth trial duration. Statistically the mean average monthly day length in January and February at the experiment site location varies from 7h to 9h approximately [17]. The occurrence of sunny skies is almost constant around 18% in average. The occurrence of intermediate skies increases from 44% to 51% while overcast decrease from 39% to 29%. This makes that the average monthly mean of hourly global horizontal PPF values have increased approximately 2,6 times from 104 to 273µmolm^{-2}s^{-1}., which means that the average PPF inside the greenhouse due to daylight radiation has increased from 62 to 164µmolm^{-2}s^{-1},at the end of the experiment. These estimations represent a maximum average daylight contribution varying between 40% and 68% in respect to the total PPF. According to practical measurements the daylight contribution to the HPS treatment was at least 2 times higher than for LED1 and LED2. It is known that the total daily PPF integral is important for increase the photosynthetic rate, leaf weight and thickness [18]. Therefore the increase of daylight availability was more beneficial for the control plants than for the LED grown plants. In spite the higher daily PPF integral in the HPS treatment due to the smaller form factor of the HPS luminaires, the highest FW and dry weight accumulation was verified for the LED2 grown plants followed by the LED1.

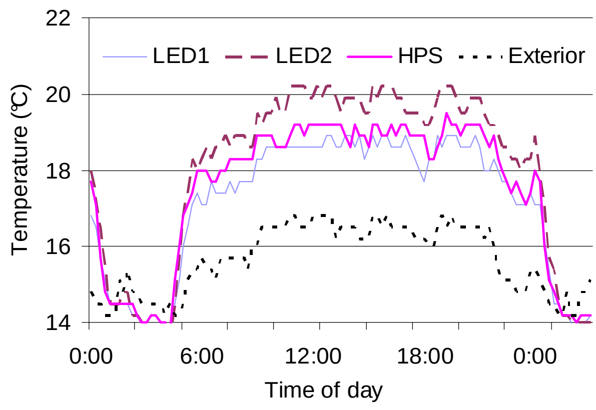

Fig. 6. Evolution of temperature at plants' canopy level for LED1, LED2, HPS and exterior between February 4th and February 7th 2005

The 1°C higher ambient temperature shown in Fig.6 measured on the LED2 side could have been beneficial for the development of the plants. Growing lettuce plants at higher temperatures have been known to increase the leaf expansion rate (LER) which improves the radiation capture and yield [19]. Thus the higher dry and fresh weight measured on LED2 for the group of plants grown under 100-120µmol^{-2}s^{-1} could had been a direct consequence of the higher ambient temperature on the LED2 treatment. On the other hand other studies have also verified that the addition of a small amount of yellow-green photons improves the final quality of certain crops where lettuce is included, suggesting the hypothesis of interdependence with the amount of blue radiation [20]-[21]. A clear confirmation of this can come from the analysis of the spectral balance of HPS lamps where a great part of its emission is in the yellow-green region (51%) while the amount of blue is approximately 5%. Additionally HPS lamps have the strongest peak emission at 569nm which is very close to the minimum absorptance value characteristic of the average green plants [22]-[23]. In spite of the effects of yellow-green radiation on crop development still aren't under unanimous contentious [16], [24]-[26], our results also suggest a possible interdependence between the influence of yellow-green and blue radiation which affects the development of lettuce plants. Although the results suggest that it might be beneficial to use of small amount of yellow radiation, it is still not totally clear if the improved results obtained on LED2 treatment is a direct result of the temperature difference or due to the beneficial effect of the yellow component or both.

IV. Conclusions

Supplemental solid-state lighting systems for greenhouses are feasible with today state-of-the-art LED devices. The biometric results gathered during the experiment have indicated that cultivation of lettuce plants in greenhouse environment using supplemental spectrum-tailored LED luminaries is possible. It was confirmed that the spectral quality of the light provided has a great importance for the crop development. The simplest spectral composition based on the two-component in red-orange and blue regions (LED1) has shown to be equally effective in enhancing the growth rate in comparison with the control plants grown under HPS lamps. An interesting result was obtained with LED2 treatment, where for the same PPF the number of leaves was the highest of all treatments.

The 20% of blue photons seemed to be effective in the inhibition of the hypocotyl elongation during growth early stages. The plants in LED1, 120-140 µmol m^{-2} s^{-1}, achieved marketable size sooner than plants in the other light treatments.

Energy efficiency is a hot topic worldwide. Higher production efficiency plays an important role in the greenhouse industry. Therefore high crop yields with low production costs are two important rules governing the horticulture industry. In commercial greenhouses in Finland, typically 30% of the total production cost is due to lighting. However, the design of efficient LED systems for plant growth should not only take into account the conversion efficiency between electrical and radiant energy but also the conversion efficiency between the radiant energy and chemical energy which is ultimately used by the plant for production of biomass. While the first aspect is mainly dependent on the electro-optical properties and performance of LEDs and drivers, the second one depends mostly on plant's photosynthetic performance. The photosynthetic utilization efficiency (PUE) evaluates the conversion efficiency from radiant energy of the light and the chemical energy [27]. LED1 treatment has shown the highest PUE with 93% followed by LED2 and HPS with 90% and 88%, respectively. PUE should be considered for economic evaluations related with supplemental lighting installation for commercial vegetable crop production. The higher PUE value of LED1 in comparison with HPS lamps directly influences the growth rate by improving the vegetative growth and green mass accumulation. In practical terms this gives an indication that LED1 treatment may accelerate the plant growth rate in half day per week. Ultimately this will reduce the time need until the crop reaches the marketable size, reduce the production cycle, increase productivity and improving energy efficiency.

In conclusion this work has given a clear indication that the growth rate of lettuce plants can be increased only with two-spectral component supplemental LED lighting containing red-orange and blue LEDs. However a third component might be as well effective and beneficial in promoting growth. The inclusion of a yellow component to a bi-component LED luminaire of basal red-orange and blue has shown higher fresh, dry-weight and higher leaf expansion rate while maintaining a balanced morphogenesis. The work has shown that an appropriated trade-off between blue and yellow radiation can further enhance the morphogenesis of lettuce, important for its successful commercialization. Although the results suggest that the tri-spectral-component LED2 treatment was more effective in promoting plant growth, further investigation has to be done to decouple and clarify the influence of 1^{o}C higher canopy temperature and the influence of the yellow component. Additionally, this study has confirmed the potentialities of LEDs as a photosynthetic light source which offers new and better possibilities for the future of solid-state lighting in horticulture. LEDs are promising light sources with potential to become in less than ten-year period, one of the main light sources in industrial production of crops. However future direct retrofitting of conventional luminaries by LED luminaries is strongly dependent on the optical photon flux density achievable. In most of the cases future applications in commercial greenhouses will continue to be ruled by economic and productivity aspects. Supplemental horticultural lighting requires very high PPF levels which can reach in Finland at least 100μmolm^{-2}s^{-1}. This value is equivalent to an illuminance of 7400lx under HPS luminaire. Commonly used lighting levels for human vision requires around 25 times less. Such high demand of photon emission and high cost of LEDs may contribute to slow down the penetration of SSL into commercial utilization for direct retrofit of conventional lighting systems in the near future. LED luminaries with high optical photon flux are required in order to be achieved small form factors which will reduce shadowing effects when used as SL. This study has contributed to give an indication of what can be achieved in a large scale commercial production. In future experiments a larger number of plants will be used in order improve the statistic results.

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