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Abstract

The first part of this work reports a growth test realized during the research project 'Kasvien valotus LED-valaistusjärjestelmällä'. This research project was carried out between the year of 2005 and 2006. The main objective of the project was to evaluate light-emitting diodes (LEDs) as photosynthetic light sources to supplement the natural daylight in real greenhouse environment. The research project was financed by the Finnish Funding Agency for Technology and Innovation (Tekes), Elektro-Valo Oy, Oy Osram Ab, Helsinki University of Technology (TKK) and the Agrifood Research Finland (MTT). The objective of the growth test was to evaluate the effects of spectral composition of the light provided by LEDs on the development of lettuce plants. LEDs with peak wavelength emissions of 630 nm and 460 nm were used. Although the control-plants grown under high-pressure sodium (HPS) lamps benefited from the higher total daily light integral due to daylight, the plants grown under LEDs were sturdier, whilst the control-plants were delicate and spindly. The higher dry weight content and the dark greener color of the leaves of the LED-grown lettuce plants, when compared with control-plants, may be an indication of higher concentration of chlorophylls. Moreover, these observations might have shown also higher light utilization efficiency by the plant resulting in higher photosynthetic activity and nutritional value. Although the results obtained for each light treatment cannot be directly compared due to the differences in temperature and daylight exposure verified, the growth test has shown the viability of usage of LEDs as supplemental light to daylight.

The second part of this work is dedicated to the evaluation and quantification of the photosynthetic radiation of artificial light sources. A proposal for a new systematization of metrics for quantification and partial characterization of the radiation used by plants in photosynthesis is presented. The denominated phyllophotometric system is developed in analogous manner as the photometric system and is based on the average photosynthetic quantum response curve of plants. A comparison of the costs of photosynthetic radiation provided by high-pressure sodium (HPS) and LED luminaire composed by red and blue LEDs is presented using the proposed metrics. The results showed that one of the aspects delaying the uptake of LED technology in horticultural lighting is the high capital cost. Although the quantification of radiation may be straightforward, its characterization and qualification has to be addressed carefully. Therefore the phyllophotometric system will be further developed and practically tested in future research work.

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1 Overview

The light emitting diode (LED) has become an important device in many areas and applications including horticultural lighting. Despite its early discovery in 1897 (Round 1907), the development work did not really start until the late 1960s (Schubert 2003). During the last two decades LEDs have been systematically evaluated as a radiation source for plant growth applications, especially in space (Massa 2005). Today they are a promising light source with large potential to become one of the main light sources in the lighting field. Their high efficiency potential in converting electrical power into optical radiant power, robustness, long life expectancy, small size and directional light emission properties are just few of the most attractive characteristics. The increase of electricity prices and the need to reduce carbon dioxide (CO_2) emissions are additional reasons to make efficient use of energy. In year-round crop production in greenhouses, the electricity cost contribution to overhead costs may reach approximately 30% share in some cultivars (Österman 2001). The use of solid-state lighting is expected to contribute to the reduction of global energy consumption by 11% by 2020 and decrease CO_2 emission between 261 to 348 million of tons over the same period of time (Tsao 2004; OIDA 2001).

The latest technological developments of LEDs have allowed their use also in applications requiring light sources with high emission of light such as in horticultural lighting. In the field of horticultural lighting the possibilities of usage are large, challenging in some cases the actual scientific knowledge in the field of plants' photobiology. It is known that even the most subtle change of the spectral composition of the light, its quantity or periodicity may trigger important physiological responses in plants. LEDs do offer the possibility of efficiently control and adjust the spectrum, the quantity and the periodicity of the light provided to plants. These possibilities give new perspectives to the food industry from which consumers are expected to benefit from. During winter in countries located at northern latitudes the weather is harsh and daylight availability is low. Therefore, supplementary light sources with improved electrical and photosynthetic characteristics are beneficial for the year-round crop production in greenhouse environment. The use of artificial light to substitute or compensate the low availability of natural light or daylight is a common practice in northern countries for production of vegetable and ornamental crops in greenhouses during the winter seasons (Dorais 2002). However, there is still space to improve the production efficiency, reduce costs and perhaps still be able to improve the quality of the crops. The utilization of more versatile, efficient light sources for plant growth can offer new and important possibilities to achieve these goals. Solid-state lighting or LED-based lighting solutions may offer this versatility and efficiency required. However, there have been several aspects hindering the use of solid-state lighting in practice. Perhaps the most important one has been the relatively high price of LEDs in comparison to conventional light sources. Other relevant aspects are related to the unconventional electrical, optical and thermal characteristics of LEDs that require the definition and standardization of several aspects such as lifetime and measurement procedures. For horticultural lighting, the situation may be even more complicated due to the lack of a widely accepted measurement system for radiation used by plants in photosynthesis (Salisbury 1991, Thimijan et al. 1983, Schurer 1997, Holmes 1985, da Costa & Cuello 2004, 2006a, 2006b). Different metrics are frequently and indiscriminately used to quantify radiation for plant growth. Radiometric, quantum, phytometric and photometric units are used to quantify and express photosynthetic radiation for plants. A future universally accepted and coherent measurement system should provide a systematic basis for units and nomenclature. The new system should consider the specificness of plant responses to the quantitative and qualitative parameters of radiation for sake of clarity and coherence with existing measurement systems. The establishment of such a system is expected to improve the accuracy of quantification and evaluation of photosynthetic radiation and allow better and more appropriate dimensioning and optimization of the lighting systems.

The uniformization of units use allow easier and more reliable comparison of performance between different lighting conditions for plant growth. Finally, the standardization, generalization, unanimous acceptance and use of a universal photosynthetic radiation metrics will avoid the unpractical, outdated and not advisable use of conversion factors.

2 Greenhouse growth test

2.1 Introduction

The main goal of the growth test was the investigation of the effects spectrally tailored LED lighting on plant growth in greenhouse environment. LED luminaries were designed and built to be used as supplementary light sources of daylight during the growth test.

The growth test was conducted at MTT's (Maa- ja elintarviketalouden tutkimuskeskus / Agrifood Research Finland) greenhouse facilities in southern Finland between February 9th and March 22nd in 2006. The experiment site is located at (60^o23'N/22^o33E) in the Piikkiö region.

The growth test was intended to be carried out during winter when the daylight availability is the lowest and when the utilization of supplemental lighting is economically viable in northern latitudes (Dorais 2002; Heuvelink et al. 2006). The experiments were conducted in one room of a twin-wall acrylic greenhouse type with a glass roof. The growth room used for both experiments was equipped with automatic control of the environmental conditions in terms of humidity, temperature and CO_2 concentration and artificial light photoperiod.

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

2.2 The LED luminaires

The LED luminaires used in the growth test were composed by a combination of red-orange and blue LEDs. The red-orange component was provided by AlInGaP LEDs (DRAGONtape^{TM}, OS-DT6-A1, *Osram Opto Semiconductors GmbH*, Germany) with peak wavelength emission at 630 nm. The blue component was delivered by InGaN LEDs (DRAGONtape^{TM}, OS-DT6-B1, *Osram Opto Semiconductors GmbH*, Germany) with peak wavelength emission at 460 nm. All LEDs used were lambertian emitters. (Osram 2004a)

2.2.1 Optical and thermal dimensioning

The spectral composition of the light provided by the LED luminaires was intended to be composed by approximately 15% of blue light and 85% of red light. In order to determine the number of red and blue LEDs required per luminaire, the photon intensity I_p [mol s^{-1} sr^{-1}] of one red and one blue LED were determined. The determination of the photon intensity took into account the driving conditions and the real operation conditions in the greenhouse.

Commonly the manufacturers of LEDs do not provide in their technical datasheets radiometric or photon quantities. Therefore in order to determine the photon related quantities, usually conversions or additional measurements have to be performed. The photon intensity was determined based on the measurement of the radiant intensity I_e [W sr^{-1}]. The radiant intensity can be either measured or derived from the manufacturer's datasheet. However in both methods the junction temperature and the operating driving current of the LEDs have to be taken into account.

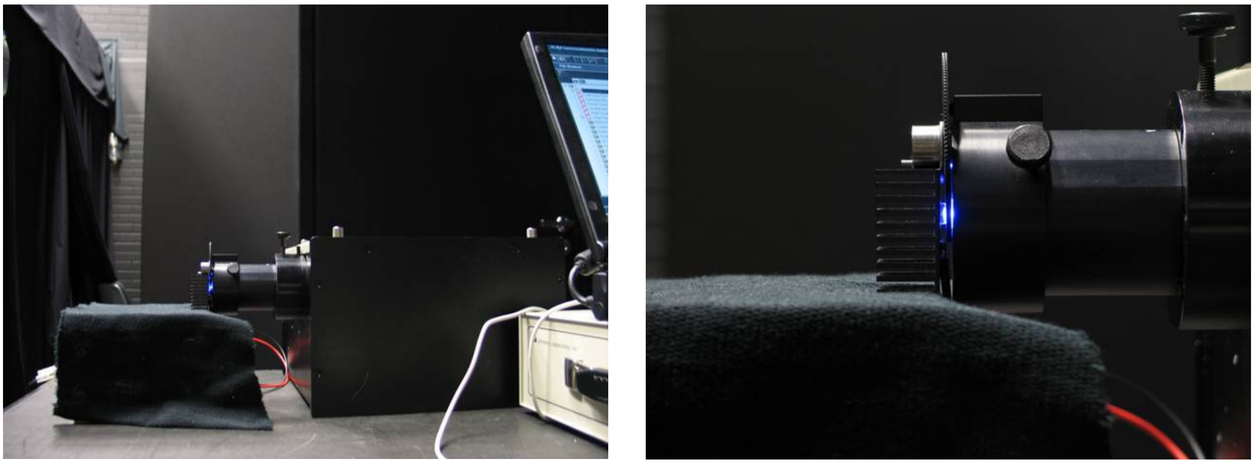


Figure 1 - Measurement set-up used to determine the radiant intensity of the LEDs under known operational conditions using a monochromator-based spectroradiometer (754-C, Optronics Laboratories Inc., USA).

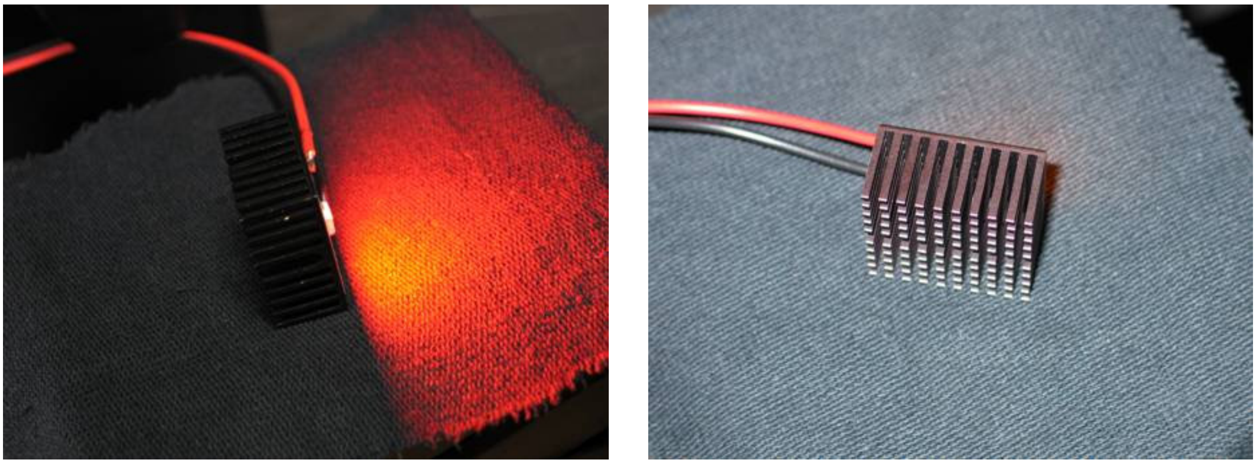


Figure 2 – Pin fin heat sink used in the thermal management of DRAGONtape LEDs during the luminous and radiant intensity measurements in order to maintain the case temperature below 40°C at ambient temperature of 25°C.

The measurement set-up for the radiant intensity is shown in Figure 1. The LEDs were placed on a pin fin heatsink from Aavid Thermalloy with a thermal resistance value of 15 K/W as shown in Figure 2. This was necessary to maintain the maximum case temperature (T_c) below 40°C, at ambient temperature of 25°C. According to the recommendation of the LED's manufacturer the 40°C of case temperature would maintain the life expectancy of the LEDs above 50 000 hours under normal conditions (Osram 2004b). The cooling surface and the ambient temperature were equal for both red and blue LEDs. However the thermal resistance between junction to soldering point and the power dissipation of blue and red LEDs were different. This implied that the case temperature was 31°C and 36°C for red and blue LED, respectively. Under these conditions the radiant intensity (I_e) for red and blue LEDs was measured and converted to photon intensity (I_p) using the following expression,

$$I_p = \frac{\lambda_{peak}}{N_A \times h \times c} \times I_e \qquad (1)$$

where N_A is the Avogadro's number ($6{,}022 \times 10^{23}$ mol^{-1}), h is the Planck's constant ($6{,}626 \times 10^{-34}$ J s), c the speed of light in a vacuum ($2{,}998 \times 10^{8}$ m s^{-1}) and λ_{peak} is the peak wavelength of the LED in meters. The measured values of the luminous and radiant intensities are presented in Table 1 together with converted photon intensity values of the red and blue LEDs.

Table 1 - Measured values of the luminous (Iν) and radiant intensities (Ie) with the converted photon intensity (Ip) values of the red-orange and blue DRAGONtape LEDs operating at case temperatures below 40°C with ambient temperature of 25°C.

LED	I_v [mcd]	I_e [mW sr^{-1}]	I_p [mol s^{-1} sr^{-1}]
Red	3647	14,6	$7{,}68 \times 10^{-8}$
Blue	2098	33,7	$12{,}9 \times 10^{-8}$

The pn-junction temperature (T_J) of the LEDs operating at case temperature around 40°C, depends on driving conditions, namely on the operating forward current of the LEDs and on thermal management of the luminaire. The junction temperature can be related to the case temperature through the simplified thermal model of the DRAGONtape LEDs shown in Figure 3. Thus, the operation temperature of the pn-junction can be determined using the following equation,

$$T_J = T_S + P_D \times R_{th,JS} \qquad (2)$$

where T_s is the temperature at the soldering point of the LED, R_{thJS} is the thermal resistance from junction to the soldering point R_{thJS} and P_D is the power dissipation of the LED. It was assumed that the case temperature was approximately the same as temperature at the soldering point (i.e. $R_{thJS} \cong R_{thJC}$).

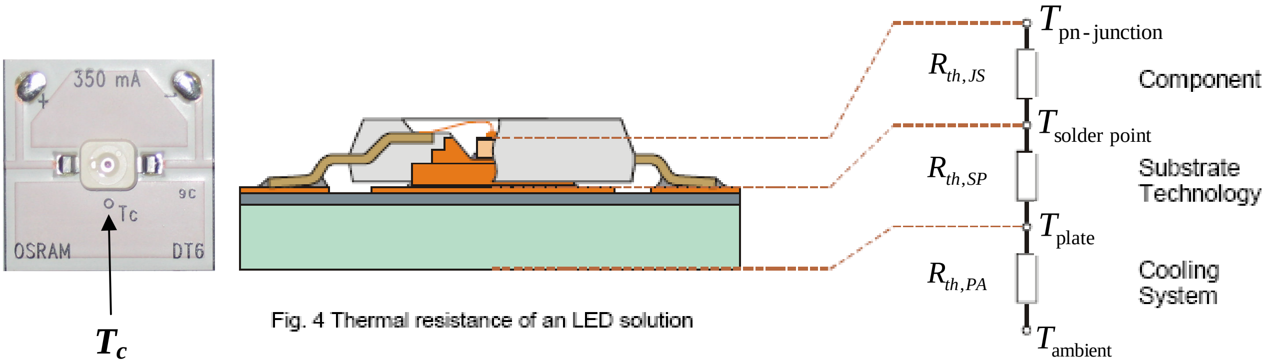


Figure 3 - Physical structure of the DRAGONtape LEDs and equivalent simplified thermal circuit.

The power dissipation of the LEDs is determined based on operation driving conditions. Considering that the power supplies provide constant and stabilized direct current (I_F) at 350mA, the equivalent forward voltage (V_F) was determined using the I-V characteristic curve of the LED given in the datasheets. With the obtained values of the forward voltage the power dissipation of the device can be obtained through the following equation,

$$P_D = V_F \times I_F \qquad (3)$$

By knowing the photon intensities of the red-orange and blue LEDs the red to blue photon (R/B) ratio can be determined. Known the percentage of blue photons need to be provided by the fixture R_{blue}, the photon intensity per red-orange LED I_{p_red}, and the photon intensity per blue LED I_{p_blue}, the ratio between the number of red-orange and blue LEDs ($N_{(R/B)}$) per luminaire can be determined using the following equation,

$$N_{(R/B)} = \frac{(1 - R_{blue}) \times I_{p\_blue}}{R_{blue} \times I_{p\_red}} \qquad (4)$$

For 15% of blue light emission the $N_{(R/B)}$ ratio obtained was 9,5. However, the dimensioning of the LED cluster of the luminaires took into consideration the uniform distribution of blue and red LEDs while maintaining their ratio as close as possible to the value calculated. The final solution for the LED cluster composition included 78 red and 8 blue LEDs. The obtained ratio in this case would be 9,75, which would slightly reduce the percentage of the blue photon flux below 15%.

The LEDs were fixed on one side of a 2-mm thickness aluminum base plate with dimension of approximately 37 cm by 22 cm as shown in Figure 4. With this LED cluster area the electrical power density and installed LED component density per luminaire was 884 W/m^2 and 814 LEDs/m^2, respectively. In spite of the higher electrical power density installed in each luminaire the implementation of passive cooling solution for the thermal management was still viable.

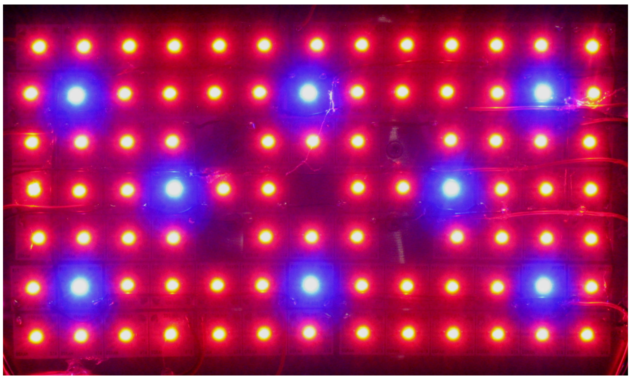


Figure 4 – Distribution of red and blue LEDs on the luminaire's aluminum base plate.

The thermal management was realized considering the guidelines for determination of the life expectancy of the LED modules given by the manufacturer. There is recommended that to maintain the life expectancy of the LEDs above 50 000 hours the case temperature T_c should not be higher than 40°C under normal operation conditions (Osram 2004b). Under normal operation conditions the maximum ambient temperature (T_a) expected in the growth room of the greenhouse was not higher than 25°C. The thermal design of the luminaire was conducted considering the previous assumptions.

Based on the thermal model circuit shown in Figure 3, the thermal resistance of the luminaire's heat sink ($R_{th,SA}$) was determined using the following equations,

$$R_{th,SA} = R_{th,SP} + R_{th,in} + R_{th,PA} \tag{5}$$

$$R_{th,SA} = \frac{T_s - T_a}{P_D} \tag{6}$$

The thermal resistance between the solder point and the ambient $R_{th,SA}$ required to maintain the T_s point below 40°C at a ambient temperature T_a of 25°C is,

$$R_{th,SA} = \frac{40-25}{72} = 0{,}2083^{O}C/W \tag{7}$$

The substrate's thermal resistance ($R_{th,SP}$) includes the thermal resistance due to the PSA of the DRAGONtape modules substrate ($R_{th,sub}$) and the thermal resistance due to the thermal paste interface ($R_{th,in}$) between the aluminium plate and the cooling system or heat sink surface ($R_{th,in}$). For sake of clarity and simplicity $R_{th,sub}$ and $R_{th,in}$ are not represented in Figure 3. Usually these type of resistances dependent on the thermal conductivity of the interface material and how well the mechanical fasting during the assembling phase of the luminaire was done. The larger the surface of the luminaire, higher will be its influence on the final thermal performance of the luminaire. The following equation was used to calculated the value of $R_{th,sub}$ and $R_{th,in}$. where l is the thickness, k the thermal conductivity and A the total area of the material.

$$R_{th} = \frac{l}{k \times A} \tag{8}$$

The 3M-Scoth 467MP PSA used on DRAGONtape LED modules has a thickness of 0,06mm with a thermal conductivity of 0,17 $Wm^{-1}K^{-1}$ (3M-Scoth 2003). The area should be approximately the same as the LED cluster which is 569 cm^{-2}. Thus, $R_{th,sub}$ value is given by,

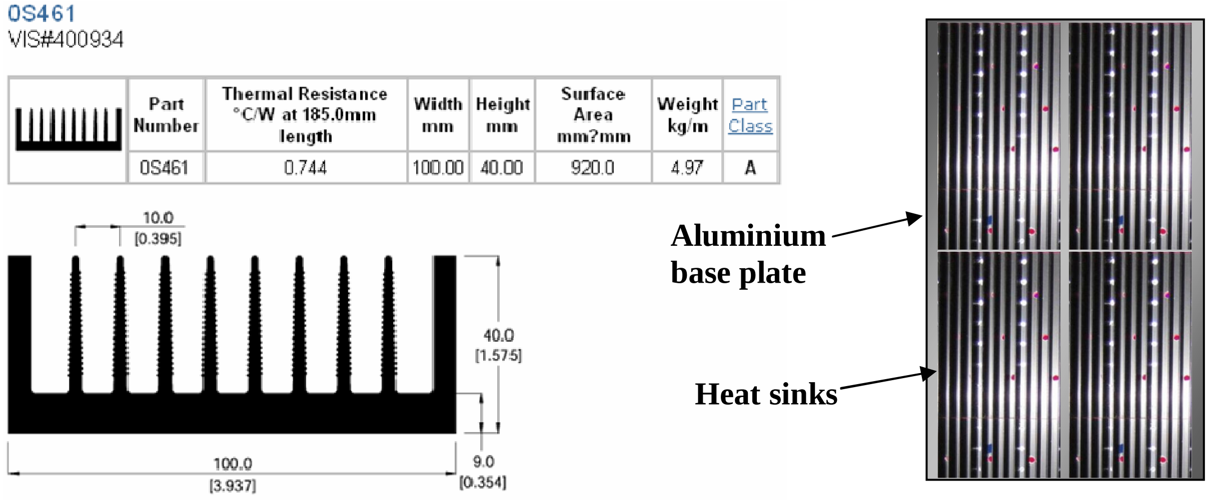
$$R_{th,sub} = \frac{60 \times 10^{-6}}{0{,}17 \times 56{,}9 \times 10^{-3}} = 6{,}2 \times 10^{-3}\, K/W \tag{9}$$

Similarly the determination of $R_{th,in}$ was done assuming that the thickness of the thermal paste used between the heat sink and the aluminum plate was 0,5 mm with a typical thermal resistance of 0,7 $Wm^{-1}K^{-1}$.

$$R_{th,in} = \frac{500 \times 10^{-6}}{0{,}70 \times 56{,}9 \times 10^{-3}} = 12{,}6 \times 10^{-3}\, K/W \tag{10}$$

Substituting the known thermal resistance values in Equation 5 the minimum required thermal resistance value of the heatsink is obtained,

$$R_{th,PA} = 0{,}2083 - (0{,}0062 + 0{,}0126) = 0{,}1895 K / W \tag{11}$$



0S461
VIS#400934

	Part Number	Thermal Resistance °C/W at 185.0mm length	Width mm	Height mm	Surface Area mm?mm	Weight kg/m	Part Class
	0S461	0.744	100.00	40.00	920.0	4.97	A

Figure 5 - Profile, physical dimensions and thermal properties of Aavid Thermalloy 0S461 extrusion heat sink (left) and the arrangement of the heatsinks on the back side of the LED luminaire's aluminium base plate (right).

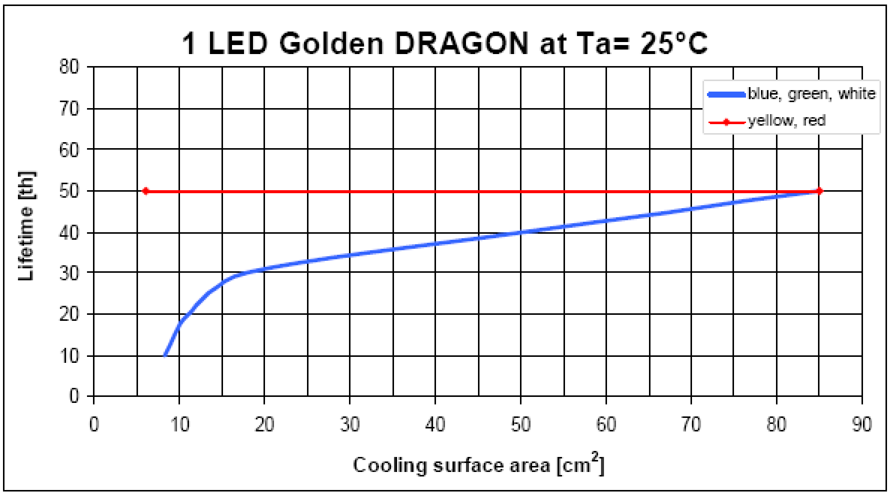


Figure 6 - Design values for the cooling surface of Golden DRAGON LEDs at ambient temperature of 25^{o}C (Osram 2004b).

Based on the previous obtained value, four black-ionized heatsinks with extraction profile from Aavid Thermalloy were chosen. Each heatsink measured 185×100×4 cm and had a thermal resistance value of 0,744 K/W. The profile, physical, thermal properties of the heat sink and its arrangement on the luminaire's aluminium plate are shown in Figure 5. This solution would provide a total thermal resistance close to the wanted value and would provide a cooling surface of 79 cm^2 per LED which is approximately the same value suggested by the LEDs manufacturer as shown in Figure 6. However an ideal value of the cooling surface would have been higher than 90 cm^2. This would increase the luminaire's profile, its weight and costs and would not bring significant increase to the optical performance of the fixture.

The LED clusters were supplied by electronically stabilized constant current power supplies modules (OT 9/200-240/350, *Optotronic*, Germany) with rated power of 8,5W and current output of 350 mA (Optotronic 2004). According to the datasheet of power supplies, a serial connection of 9 red LEDs or 6 blue LEDs could be powered by each module. The power supply boxes containing the power supply modules were placed remotely at approximately 40 cm above the LED luminaires. In each LED growth block ten LED luminaries were installed, requiring 780 AlInGaP red-orange and 80 InGaN blue LEDs. All luminaries were assembled at Elektro-valo Oy facilities in Laitila, Finland.

2.2.2 Optical and thermal performance

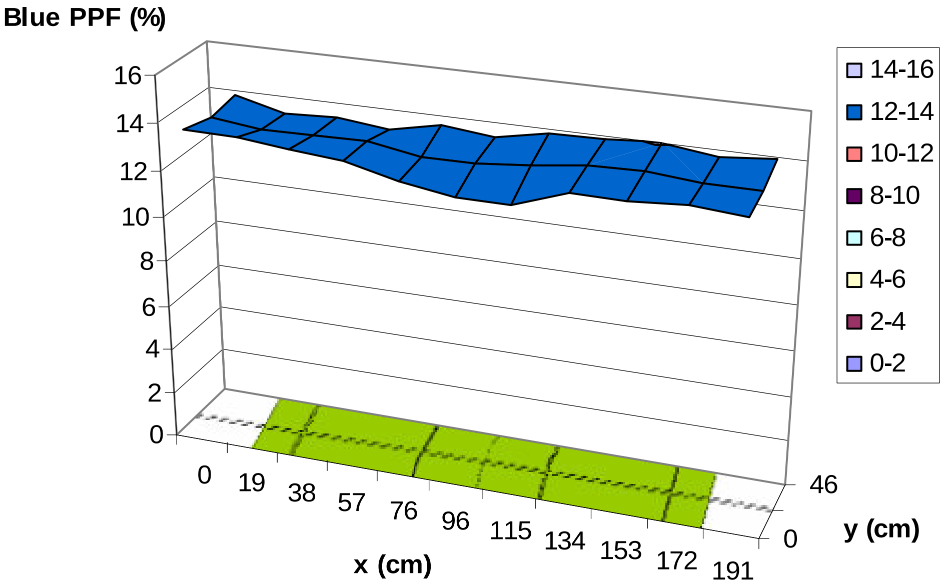


Figure 7 – Distribution of the blue PPF distribution in percentage of the total PPF at the growth areas measured in dark-room conditions.

Based on photosynthetic photon flux (PPF) measurements performed in dark-room conditions, the ratio between the blue and red light component was determined. Was verified that PPF R/B ratio was almost constant along throughout the growth areas as shown in the Figure 7. The average percentage of blue light was approximately 14% of the total PPF and the uniformity distribution on the growth area was almost constant.

The surface representation of the PPF distribution measurement at 30-cm distance from the LED luminaries in dark room conditions is shown in Figure 8. The light uniformity on the growth areas represented in green was around 73%.

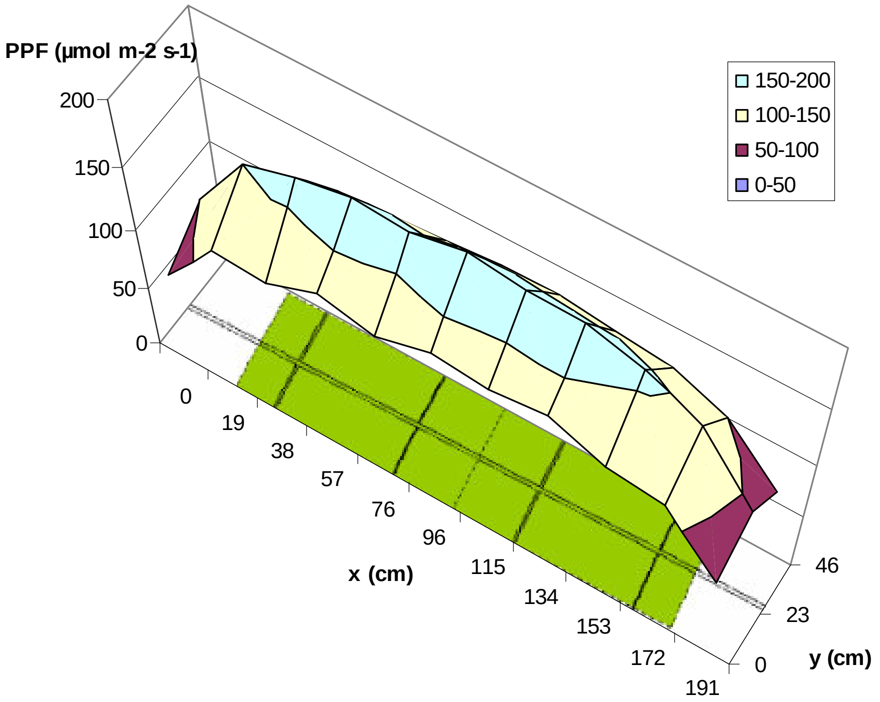


Figure 8 - Surface representation of the PPF distribution measurement at 30-cm distance from the LED luminaries in dark room conditions.

The thermal performance of LED luminaires may be decisive in terms of optical performance and reliability of the system. The lower the operation temperature of the pn-junction, the higher will be the life expectancy of the LEDs. Therefore removing the heat away from the pn-junction through an appropriated thermal management of the luminaires is desirable.

The LEDs used on the luminaries had electrical efficiencies between 8 and 14% at junction temperature of 25°C. Considering that the luminaries in greenhouse environment had case temperatures T_c between 49°C and 52°C the correspondent electrical efficiencies of LEDs drops to 5 and 12%. These efficiencies represent a significant amount of heat released by the luminaires in each growth block, considering the total electrical power consumption involved. Although most of the heat was conducted way from the LEDs and released to the ambient through the heatsinks on the upper part of the luminaires, some heat was also released to the air from the LED cluster side. In dark room measurements was verified that the ambient temperature at 30-cm below the LED luminaires has increased around 6°C due to the heat released by the luminaires in each block. However in real greenhouse operation this increase of the ambient temperature at canopy level was insignificant due to higher circulation of air.

Around 12% decrease on the average PPF was observed due to the increase of operation temperature of the pn-junction since the switch-on moment (i.e. cool operation) until the thermal equilibrium is achieved two hours after switch on (i.e. warm operation). The peak wavelength of red-orange LEDs shifted around 2 nm towards longer wavelengths also as a result of the increase of temperature at the junction. The decrease of the PPF and the shift of the peaks wavelength of the red-orange and blue LEDs can be observed in Figure 9.

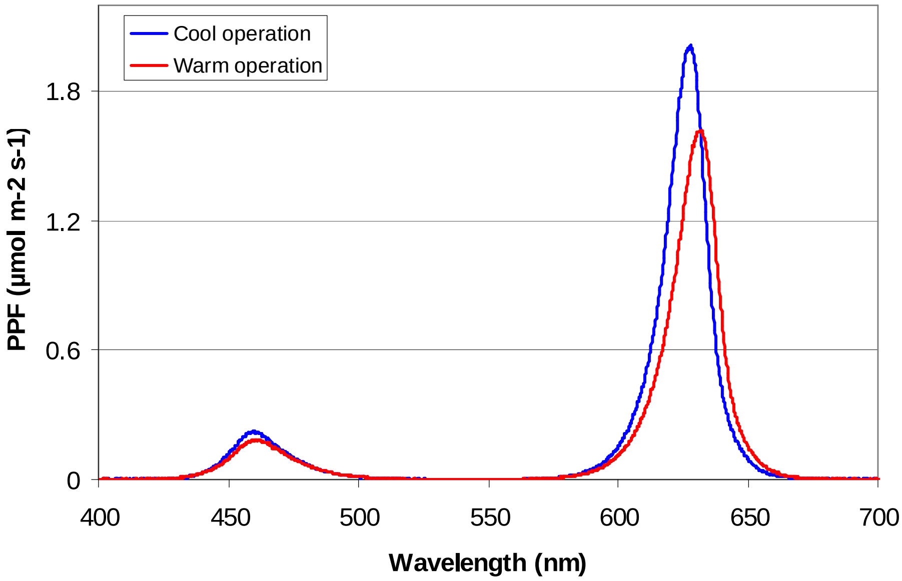


Figure 9 – Spectral PPF distribution curves in dark room conditions measured immediately after switch-on (cool operation) and 2 hours after switched-on (warm operation).

2.3 High-pressure sodium lamps

The lighting system used to grow the control-plants was composed by two 400-W tubular clear high-pressure sodium lamps (MASTER SON-T PIA Plus E, *Philips Lighting*, Netherlands) and respective fixtures. This lamp has a total luminous output of 56500 lm (i.e., approximately 762 µmol s^{-1}), with a correlated colour temperature of 2000K. The lifetime expectancy is 20000 hours (Philips Lighting 2004).

The arrangement of the luminaries in the experiment site is shown in Figure 10 together with the spectral irradiance on the central point on the irradiated area under the lighting system. The control-plants grown under the HPS lighting system were used as reference for evaluating the growth performance of the LED-grown plants.

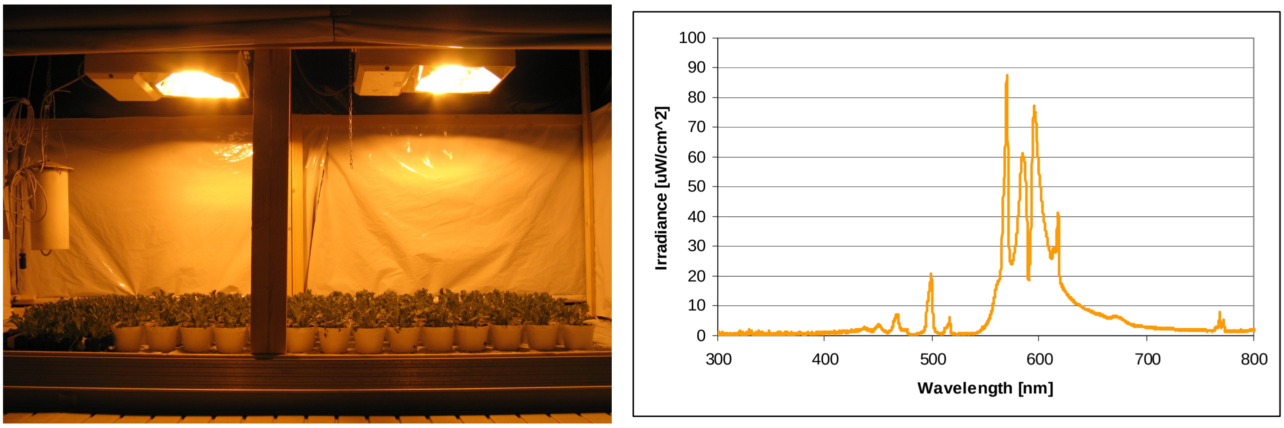


Figure 10 – Lettuce plants growing under the HPS lamp system in greenhouse at MTT, Piikkiö March 1st 2006 (left) and spectral irradiance distribution of the central point on irradiated area under the lighting system (right).

2.4 Experiment set-up

The growth test was conducted in one the growth room of the greenhouse equipped with automatic control of room's humidity, temperature and CO_2 concentration and lighting photoperiod. The dimension of the growth room was approximately 7,5 m long by 6,2 m width.

The experiment set-up of the growth test was composed by four growth blocks where two were used to grow the control plants under HPS lamps and two other growth blocks to grown plants under LED lighting. The HPS and the LED luminaires were installed approximately at 90 cm and 32 cm, respectively, above the plants' pots. In each growth table one LED and one HPS lighting system were aligned side by side and surrounded by white reflective curtains as shown in Figure 11.

Figure 11 – Panoramic view one of the LED (left) and HPS lighting systems composing the experiment set-up in the greenhouse at MTT in Piikkiö on March 1st 2006, 7:29 am.

The curtains were used intended to limit the amount of daylight and other stray light interference on the lit area. Additionally, the curtains were also useful to reduce the light waste and enhance the PPF uniformity distribution on the lit area.

The arrangement of the four growth blocks inside the room at the greenhouse is shown in more detail in Figure 12. Two tables with 600 cm long by 140 cm width were used to place the lettuce plants under the lighting systems. The size of the LED growth blocks was 45 cm by 200 cm. Because of technical reasons each growth block was divided in two growth areas represented by the green area in the Figure 12. In total there were four growth areas for each lighting treatment. The growth areas are referenced as LED1, LED2, LED3, LED4, HPS1, HPS2, HPS3 and HPS4 in Figure 12. The plants used for statistic analysis were grown inside these areas. The average PPF used was 180 µmol m^{-2} s^{-1} and equal in all growth areas, therefore the area size was of each was of 40 cm x 70 cm.

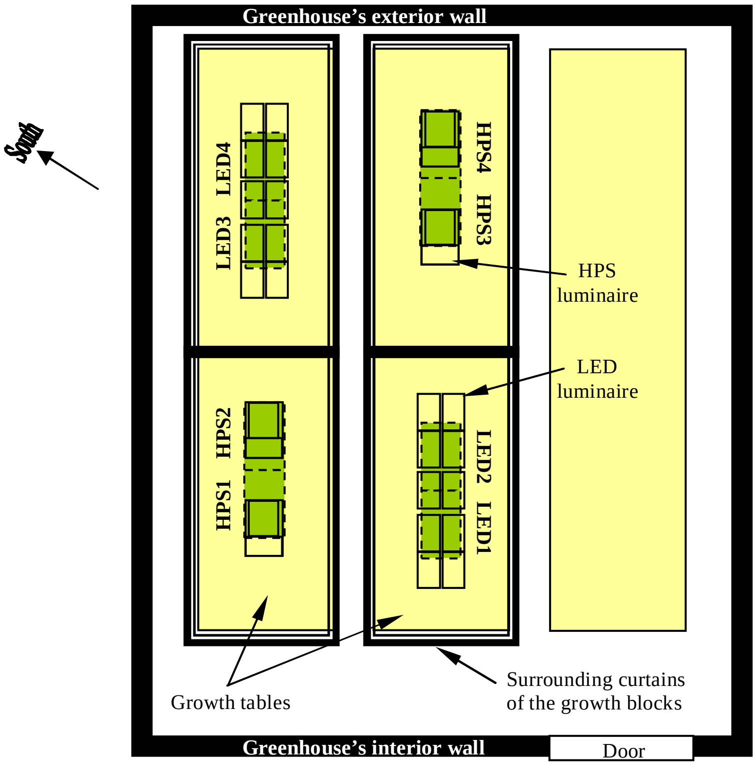


Figure 12 – Top-view of the arrangement of the experiment setup arrangement inside the growth room representing in green the growth areas LED1, LED2, LED3, LED4, HPS1, HPS2, HPS3 and HPS4 composing two LED and two HPS growth blocks.

The growth blocks were surrounded by the 175-cm height black-white plastic curtains. The interior and exterior part of the curtains was white until 1 meter height. The highest part of the interior was black with the purpose of absorbing the incoming diffuse daylight. On the north-west wall of the room was hang a white plastic to reduce the influence of natural daylight which at that time of the year was higher than was desirable. Therefore, also the shadowing curtains on the roof of the greenhouse were shut during whole test.

The distribution of the PPF varied in each area. In the beginning of the growth test the PPF measurements were done in each 10 cm. According to this the location of the growth areas was determined. The growth areas under the LEDs were centered with the LED luminaires. The growth areas under the HPS lighting were not exactly in the same place in relation to the HPS luminaires.

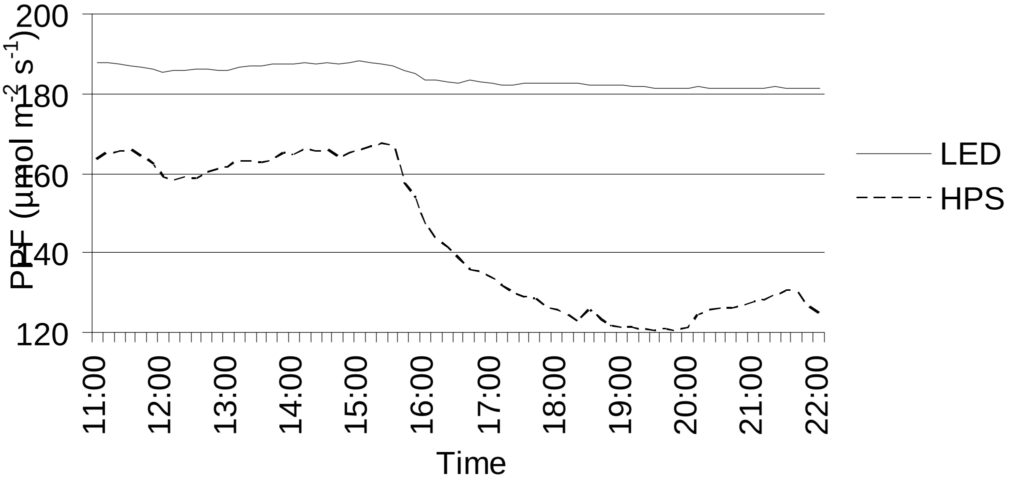


Figure 13 - PPF measured at the center of LED4 and HPS4 growth areas on March 6th 2006 between 11 am and 10 pm.

The lighting conditions were not the same during whole growth test. The natural daylight increased towards the end of the test. Figure 13 shows the PPF evolution at a measuring point of the growth area LED4 and HPS4 during a sunny day. The notorious decrease of the PPF level of the HPS4 after 4 pm, might have been caused by the shadow created by the lettuce leaves on the meter head or by unintentionally move of the growth table causing the change of the location of the meter head in relation to the light sources or by the malfunctioning of the PAR meter. The leaves of lettuce plants grown under LEDs were not so big that they could have changed the measurement results. During sunny days the LED luminaires were causing more shadowing effects than HPS luminaires. Even though the day was sunny the PPF level has not increased due to the shadowing caused by the LED luminaires as it can be seen also in Figure 13.

Because of the fixing work of one of the LED luminaires their position was altered and as a result the illumination was on permanently from 10.30 am on March 1st to 1.00 pm on March 3rd for both LED growth blocks.

The LED luminaires did not warm up during its use and the light level did not decrease significantly after turn on as shown in the Figure 14. After 9 am clock the curtains of the blocks were raised causing changes on PPF level.

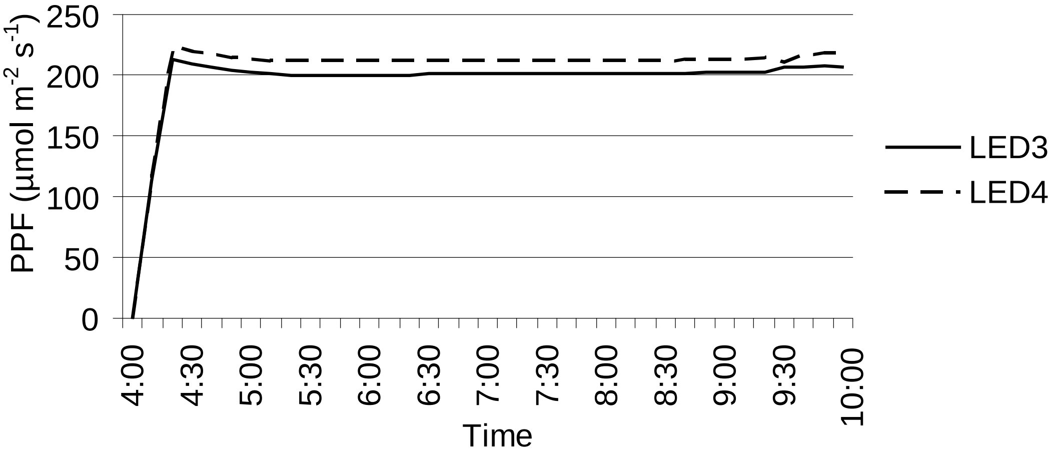


Figure 14 - Kuvio 10. Evolution of PPF at a point located at plants' pot level of LED3 and LED4 growth areas on March 1st 2006 (week 3) between 4 am and 10 am.

2.5 Material and methods

Lettuce plants were grown in peat substrate (Kekkilä B2S, Finland). Three lettuce plant seeds were in each pot. The shoots grew under black-white plastic in the darkness at ambient temperature of 16°C. The pots were placed 3 days after planting on the growth areas after most of the lettuces had been shooting. Watering carpets were placed under the pots. The plants were watered by the top as long as it was possible and then after from the bottom. At this point the lighting was started using a photoperiod of 20 hours light, between 4 am and 12 pm, and 4 hours dark. The plants were fertilized according to Kekkilä's guidelines.

The shoots were placed in white pots with a meshed bottom and 12 cm of diameter two after lighting as started. Every week the plants were removed from the growth areas in order to give space for the other plants to grow and to be measured.

The ambient temperature and the relative humidity were followed in each growth block. The sensors were localized under the luminaires, first on the growth tables and afterwards at pots' upper part between the plants. The psychrometer, which registered the environmental parameters of the room, was located inside of one of the HPS blocks.

Figure 15 shows the average ambient temperatures on the LED and HPS growth areas during the whole test duration.

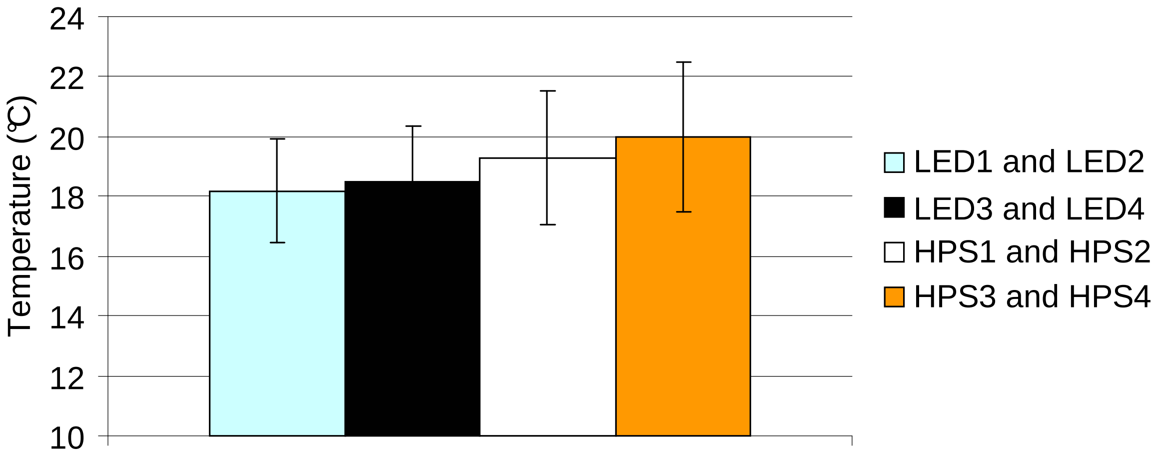


Figure 15 - Average ambient temperatures and standard deviations of the LED and HPS growth areas during the whole test duration.

In the beginning, when the shoots were growing, 30 plants were chosen uniformly from the growth areas. The location of these plants changed slightly after each measurement, because they were relocated uniformly across the growth areas. Approximately two weeks after planting the first measurements of the hypocotyl elongation, leaf areas, fresh and dry weight of six plants were done. The following day the rest of the plants were placed in pots. After one week on March 1st, the length of the leaves, their number, fresh and dry weight was measured. From the third measurement forward the number of the leaves, fresh and dry weight was measured weekly.

The temperature of the leave surface was measured four times at week 2, 3, 4 and 5 using a non-intrusive thermometer (Microscanner D501, *EXERGEN*, USA). From every growth area the temperatures of the leaves of six plants were measured.

2.6 Results

At week 2, the plants grown under the LEDs showed hypocotyl lengths with half of the size of the control plants grown under the HPS lamps as shown in Figure 16. The LED-grown plants were sturdy whilst the control plants were delicate and spindly. The leaf area of the control-plants was larger than the LED-grown plants. The leaf area of the LED- and HPS-grown plants was 27,3±6,1 cm² and the 39,1±7,9 cm², respectively.

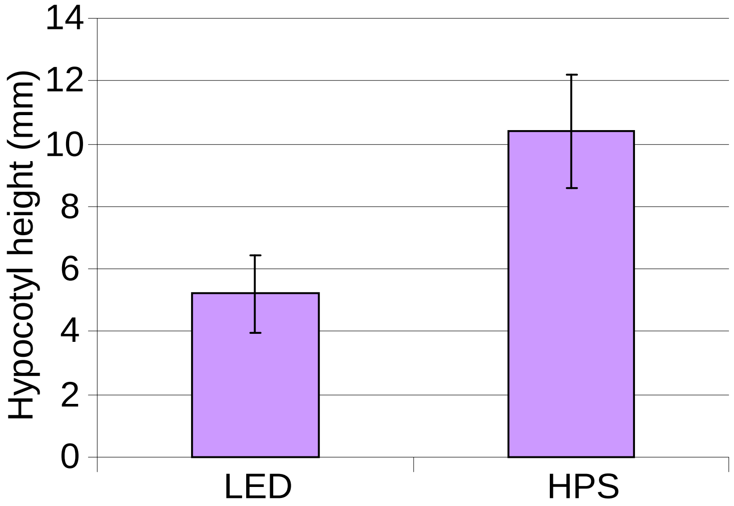


Figure 16 - Hypocotyl height of LED- and HPS grown plants at week 2 on February 22nd 2006.

Figure 17 - Lettuce plants grown under LEDs (left) and under HPS lamps (right) 3 days after planting.

Table 2 - Average number of leaves per lettuce plants grown under LED and HPS lamps between March 1st (week 3) and March 22nd (week 6) 2006.

	Average leaf number per plant	
Plant age (week)	**LED**	**HPS**
3	4,7	4,6
4	7,1	7,3
5	9,4	10,0
6	11,5	12,5

Three days after planting the leaves were longer in plants grown under HPS lamps as shown in Figure 17. The length of the LED- and HPS-grown lettuce leaves was 8,1±0,4 cm and 10,2±0,4 cm. The measurement of the leaves areas and length was not followed after this. At this stage the number of leaves was slightly higher for plants grown under LEDs. The following three measurements have shown that control plants had more leaves than plants grown under LEDs as shown in Table 2.

During week 2 and week 6 the fresh weight was always higher for the control plants than for the LED-grown plants. The relative fresh weight differences during these weeks did not suffer significant changes as shown in Figure 18.

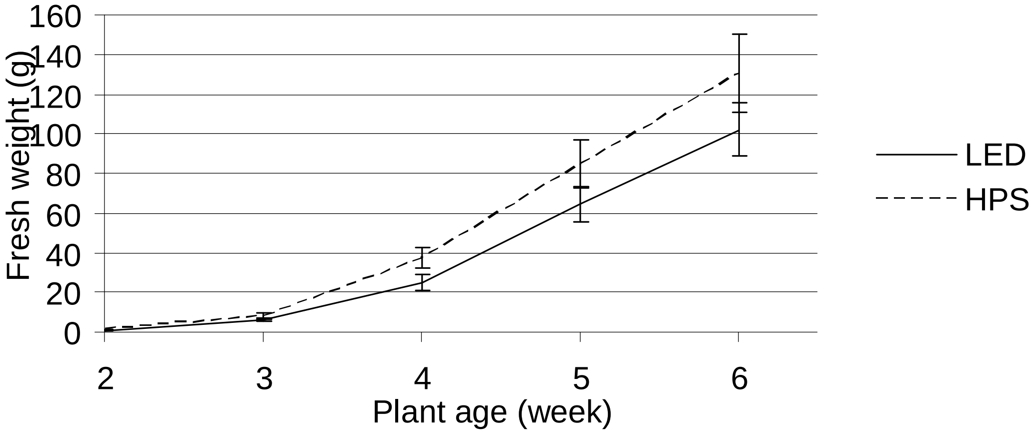


Figure 18 - Evolution of the fresh weight for LED and HPS-grown plants between week 2 and week 6.

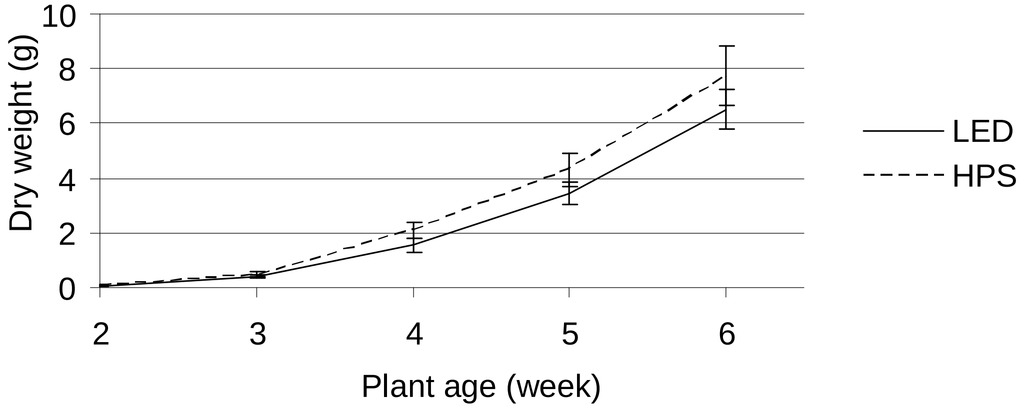


Figure 19 - Evolution of lettuce dry weight per shoot and standard deviation during the growth test duration for plants grown under LEDs and under control lighting (HPS).

The dry weight of plants grown under HPS lamps was always higher than the LED-grown plants as shown in Figure 19. However, the percentage of dry weight was during the whole duration of the growth test higher for lettuce plants grown under LEDs as shown in Table 3. At beginning of the growth test the dry weight percentage of LED-grown plants was 11% higher than control-plants. One week later the difference was of 5% and on the following week of 9%. At the end of the growth test the dry weight percentage was 6% to 7% higher for plants grown under LEDs in comparison to plants grown under HPS lamps.

Table 3 - Evolution of the percentage of dry content for plants grown under LED and control lighting (HPS) during whole test duration.

	Plant's dry weight content (%)	
Plant age (week)	**LED**	**HPS**
2	6,24	5,62
3	6,35	6,03
4	6,17	5,68
5	5,38	5,08
6	6,37	5,93

There wasn't verified any significant differences on the temperature of leaves between the two light treatments. The temperature measurement of the leaves was done during sunny days and also during cloudy days. During the first measurement on February 21st the temperature of the leaves of plants grown under HPS lamps was of 19˚C whilst for the LED-grown plants' the temperature was 0,8˚C lower. In the next measurement performed on February 27th the temperature of the LED-grown plant leaves was of 17,9˚C, whilst for the HPS-grown plants the temperature was 0,4˚C lower. The following measurement revealed the same leaf temperature difference between the HPS and LED-grown plants. In the second last measurement the leaves temperatures was higher for plants grown under HPS lamps and on the last measurement for plants grown under LEDs. The leaf temperatures varied between 17,9˚C and 19,4˚C.

2.7 Discussion and conclusions

It is important to maintain the abiotic conditions similar in comparative plant-growth experiments. The ambient temperature and the total daily light integral were among the relevant environmental factors. Due to the different form factor, shape, PPF and spatial pattern distribution characteristics of the luminaires, the daylight contribution to the LED blocks was less than to the HPS blocks. The different optical, electrical and thermal characteristics of LEDs result in different optical characteristics of LED luminaires compared to conventional HPS luminaries. 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 under the high-pressure sodium luminaires, which might have benefited the growth of the control plants.

The realization of the growth test near to spring time weakened its reliability. This was due to the higher daylight availability and the consequent influence on the final results, in spite of the use of 175-cm height curtains around the growth blocks and the shadowing curtains on the roof were closed. The quantity and quality of daylight contribution to the total PPF varied according to the weather conditions. It is known that the total daily PPF integral is important for the increase of the photosynthetic rate, leaf weight and thickness (Chabot et al. 1979). Therefore, the higher shadowing effect on LED-grown plants might have limited its capacity for biomass accumulation in relation to control-plants. Therefore, the increase of daylight availability was more beneficial to the control plants than to the LED-grown plants.

Additionally, the higher amount of heat emitted by the HPS lamps influenced the development of control-plants. The ambient temperature differences between the LED and HPS growth blocks had a significant influence on different development of the lettuces in each block. Growing lettuce plants at higher ambient temperatures is known to increase the leaf expansion rate, which improves the radiation capture and yield (Frantz et al. 2001). Thus, the higher fresh weight of control-plants could have been a direct consequence of the higher ambient temperature of the HPS blocks. The highest average temperature difference was found between LED1/LED2 and HPS3/HPS4 growth blocks, with almost 2^{o}C. According to the initial plan of the growth test, the environment temperature should have been the same in all growth blocks. However, this was impossible to achieve when there was the need of substitute the 70-W HPS luminaires by higher power 400-W HPS luminaires. The use of more powerful HPS luminaires resulted on the need of placing the luminaires at higher height reinforcing the influence of diffuse daylight on development of control plants. The raising of the blocks made it even more difficult for the air circulation. Moreover, the psychrometer, which controlled the ambient temperature and the relative humidity of the growth room, was located on the HPS growth block. In this way all the settings related with environmental conditions of the room were regulated according to the conditions of the control blocks.

Because of the reasons mentioned above, the results are not comparable and therefore no reliable conclusions can be made based on these. Nevertheless, the results of the growth test clearly indicated that the use of red-orange and blue LEDs can at least achieve similar growth performance in terms of biomass production to that of HPS lamps in year-round lettuce cultivation. Additionally, it should be remembered that this performance was achieved using approximately 30% less optical radiant power per unit area of growth than used to grow the control plants using high-pressure sodium lamps. This proves the energy-efficiency potential offered by LED-based systems in plant growth. Moreover, by visual observation of the plants grown under LEDs were slightly more darker green than the control plants during the whole test (Figure 20), which indicates that the chlorophyll contents was higher than of the control-plants. Therefore, greener colour of the leaves grown under the LEDs might have been a result of the higher photosynthetic activity and therefore higher energy utilization efficiency by the plants.

Figure 20 - Lettuce plants grown under HPS lamps (left) and under LEDs (right) six weeks after planting on March 22nd 2006.

3 Evaluation of the photosynthetic radiation

3.1 Introduction

The development of solid-state lighting has been seen with increasing interest and expectations. However its practical application has been hindered by several aspects. Perhaps the most important one has been the relatively high price of LEDs in comparison with conventional light sources. Another important aspect is related with the unconventional electrical, optical and thermal characteristics of LEDs which requires the definition and standardization of several aspects such as lifetime and measurement procedures. In horticultural lighting the situation might be slightly more complicated due to the lack of a widely accepted measurement system for radiation used by plants in photosynthesis (Salisbury 1991; Thimijan 1983; Schurer 1997; Holmes 1985; da Costa 2004, 2006a, 2006b).

Due to the photosynthetic potential, energy saving potential, fast technological evolution and reduction of prices, solid-state is foreseen as one of the preferred solutions for horticulture applications in the future. Considering the existing scenario and the urgent need for standardization in SSL field and in plant radiation measurements, it is perhaps the right time to work towards a universally accepted and coherent measurement system which can provide a systematic basis for units and nomenclature. The new measurement system should consider the specificness of plant responses to the quantitative and qualitative parameters of radiation for the sake of clarity and coherence with existing photometric system. The existence of such system would allow a fair evaluation of plant productivity and the efficiency of growth facilities and installations and consequently their optimization. The possibility of more rational use of energy and reduction of costs will be reinforced by a more appropriate evaluation and selection radiant spectrum to be used. The uniformization of units will allow easier and more reliable comparison of performance between different lighting conditions for plant growth. Finally, the standardization, generalization, unanimous acceptance and use of a universal photosynthetic radiation metrics will avoid the unpractical, outdated and not advisable use of conversion factors.

3.2 Background

The existing metrics and methods for quantify and qualify radiation used by plants in photosynthesis are very confusing. Radiometric, quantum, phytometric and even the photometric metrics are frequently and indiscriminately used to quantify radiation for plant growth. As an example, Figure 21 shows how various measurement systems spectrally quantify the amount of sunlight following on a horizontal surface.

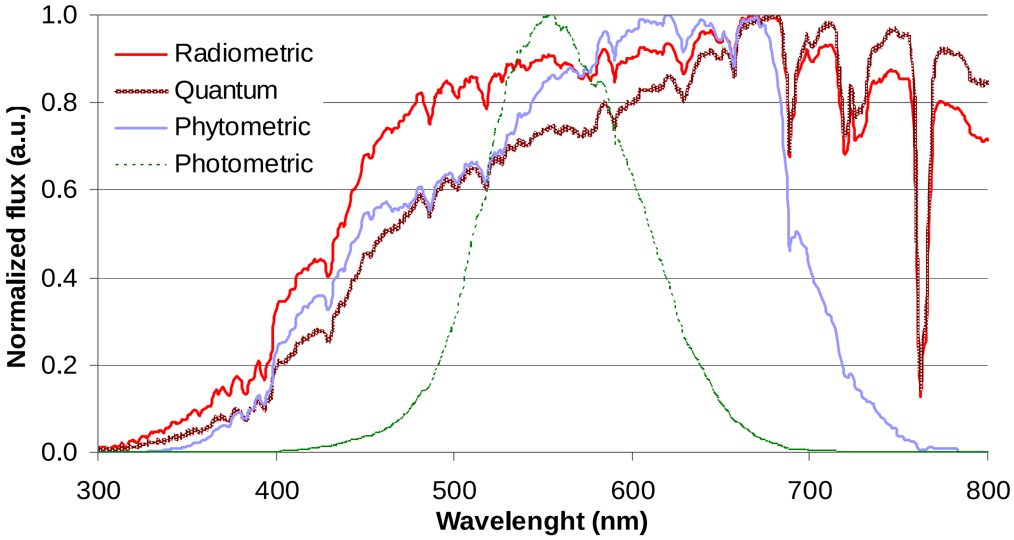


Figure 21 - Comparison of normalized spectral flux density distribution of sunlight evaluated by the radiometric, quantum, phytometric and photometric equivalent metrics.

The radiometric system, which is the basis of the photometric system, uses radiance power as the basic quantity and watt (W) as the basic unit. This quantity represents the flow rate of radiant energy in joule (J) per unit time or second (s). However radiant energy does not properly correlate with the photosynthetic rate (McCree 1972; CIE 1993a). This is mainly due to the photochemical characteristics of the photosynthesis process.

The photometric system and its quantities and respective units was developed to measure radiation for vision (i.e., light). The photometric system is based on the SI (International System of Units / Systèm International d'Unités) basic unit, candela (cd), which is a measure of the luminous intensity (I_v). Along with candela the other six SI basic units are metre (m), kilogram (kg), second (s), ampere (A), Kelvin (K) and mole (mol). Candela has been defined by the Coférence des Poids et Measures (CGPM) in 1979, as the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540 x 10^{12} hertz (Hz) and that has a radiant intensity in that direction of 1/683 watt (W) per steradian (sr) (CIE 2004). Until now, the photometric system has been the only system formally defined for the measurement of photobiological quantities in the SI (BIPM 2006). This can still be one of the main reasons why the photometric, radiometric and quantum systems are indiscriminately used in quantification of optical radiation for plant growth. The use of the photometric system as a metrological system for quantification of radiation for plants should be avoided because its quantities and units are based on the spectral luminous efficiency functions for the human eye $V(\lambda)$ and $V'(\lambda)$, for photopic and scotopic vision, respectively. Therefore it does not correlate with photosynthetic rates due to the different spectral response curves to radiation.

The quantum system uses the unit of amount of substance, mole (mol), to quantity the amount of photons or quanta. The quantum system response ideally weights all photons equally and is based on the Stark-Einstein law which directly relates the amount of photosynthetic photons incident on a plant leaf with the amount of chemical change in molecules (Hart 1988). The quantum system is one which best correlates with photosynthetic rates because of the photochemical nature of photosynthesis. However it does not take into account the photosynthetic spectral sensitivity of plants. Moreover the sensors used are based on photodiodes, which have their spectral responsivity response measured in amperes (A) of photocurrent generated per watt of incident radiant power. Typically the spectral response of silicon photodiodes matches well with radiation emitted from ultraviolet to the near infrared region (APT 2008). However, this response can be altered by tailored made windows or filters. Therefore, it is possible to find quantum sensors with different spectral responses including the ones where photons are weighted equally due to the flat spectral response of the sensors used. McCree, in 1965, was calling for attention to the fact that there wasn't any evidence at the time that plants have a linear response to radiation (McCree 1965). During early seventies, several measurements have been performed and a comprehensive set of data has been gathered (McCree 1972a, 1972b). For that, the action spectrum, absorbance and spectral quantum yield of CO_2 uptake was measured for leaves of 22 species of crop plant, over the wavelength range between 350 nm and 750 nm. The spectral quantum yield curve, which represents the rate of photosynthesis per unit rate of absorption quanta has been replicated by Inada and later refined and renamed by Sager as the relative quantum efficiency (RQE) curve (Inada 1976; Sager 1982, 1988). This data was the basis in establishing the CIE recommendations which defined the wavelength bandwidth for photosynthetically active radiation (PAR) measurements between 400 nm and 700 nm (CIE 1993b). PAR is often used to quantify and characterize the radiant energy absorbed by plants.

The phytometric system has been the latest proposal intended to be used as universal basis for plant photometry (Costa 2004, 2006a, 2006b). The phytometric system has been claimed to be developed in analogy with the photometric system using the RQE as photosynthetic spectral response. However, this system and its main unit 'phytoW' is derived based on spectral power distribution (SPD) of the light source and the RQE curve which represents the rate of photosynthesis per unit rate of absorption of quanta. In addition, it is known that the photosynthetic rates correlates better with the quanta measurements than with energy due to the photochemical characteristics of photosynthesis (i.e., photon and molecule interaction) (McCree 1972a, CIE 1993b). Thus it seems not reasonable to substitute one measurement system which does not take into account the photosynthetic response curve of the plants by another which does not correlate well with photosynthetic rates and is based on radiant energy measurements. Therefore, the use of the phytometric system it seems not an acceptable metrological system to be used for plant growth.

3.3 The phyllophotometric system

It is widely accepted that, "*units and quantities describing biological effects are often difficult to relate to units of the SI because they typically involve weighting factors that may not be precisely known or defined, and which may be both energy and frequency dependent.*" (BIPM 2006) However, taken into consideration the intensive work carried out to establish the mean photosynthetic response curve of plants, an attempt is here made to develop a coherent and systematic metrics for photosynthetic radiation.

Phyllophotometric is the denomination for the new system and comes from the from the Greek words '*fyllo*', '*fotos*' and '*metrikos*' which means '*leaf*', '*light*' and '*metric*', respectively. The proposed system is based on the relative photosynthetic yield quantum spectral response curve RQE, which was established based on the photosynthetic rate measurement results of 25-mm^2 plants' leaf sections. Although not the most important issue, the denomination of a system and its units and the terminology should give an indication, whenever possible, of its origin and nature. Misnomers may be misleading and create wrong conception in relation to the origin of the system, unit or quantity been measured.

The phyllophotometric system is based on the quantum or photon system, taken into consideration the dependence of photosynthetic rates on the number of photons falling on the leaf area per unit time. Photosynthesis is mainly driven by the number of photons. Photons with different energies induce different metabolic responses and photosynthetic rates.

The development and presentation of the phyllophotometric system is done in analogous manner as the CIE system of physical photometry (CIE 2004). The main quantity, the phyllophotometric flux (ϕ_{ps}), can be derived from its quantum equivalent unit, the photon flux (ϕ_p), measured in photon quanta per second (mol s^{-1}) or from the radiometric fundamental physical quantity, the radiant power (ϕ_e), measured in watts (W). In both cases ϕ_{ps} is derived by evaluating the radiation emitted by a source according to its action upon the relative photosynthetic RQE curve. The phyllophotometric flux can be derived using the following expression and the unit proposed for its quantification is phyton (pt).

$$\phi_{ps} = K_y \int_{\lambda=300nm}^{\lambda=800nm} \phi_{p,\lambda} P_y(\lambda) d\lambda \qquad (12)$$

where $P_y(\lambda)$ represents RQE curve, $\phi_{p,\lambda}$ is the spectral photon flux distribution and K_y is an arbitrary. The arbitrary constant K_y was chosen to be 100 × 10^{-12} and can be related to a monochromatic radiation with a frequency of 491 × 10^{12} Hz corresponding to the wavelength of 610,575 nm with a photon intensity in that direction of (1/100) × 10^{-6} mol s^{-1} sr^{-1}. This yield,

$$K_y = \frac{100\left[pt \cdot s \cdot mol^{-1}\right]}{P_y(610{,}575\,\mathrm{nm})} = 100\ pt \cdot s \cdot mol^{-1} \qquad (13)$$

In case the spectral photon flux distribution ($\phi_{p,\lambda}$) of the radiation source is not known, the spectral radiant power distribution ($\phi_{e,\lambda}$) should be used instead, applying the following equivalent expression,

$$\phi_{ps} = K_y \int_{\lambda=300nm}^{\lambda=800nm} \frac{\lambda}{N_A hc} \phi_{e,\lambda} P_y(\lambda) d\lambda \qquad (14)$$

where N_A is the Avogadro's number (6,022 × 10^{23} mol^{-1}), h is the Planck's constant (6,626 × 10^{-34} J s), c the speed of light in vacuum (2,998 × 10^{8} m s^{-1}) and λ the photon's wavelength in meters (m). For numerical calculations, the maximum peak wavelength value of $P_y(\lambda)$ function located at around 611 nm should be used.

The phyllophotometric efficiency $K_{ps}(\lambda)$ for monochromatic radiation uses phyton second per mol (pt s mol^{-1}) as unit and can be calculated using the following expression,

$$K_{ps}(\lambda) = K_y \cdot P_y(\lambda) = \frac{\phi_{ps}}{\phi_p} \qquad (15)$$

where the maximum values of $K_{ps}(\lambda)$ is given by the arbitrary constant K_y. This value is equivalent to light energy utilization efficiency as defined by Sager (Sager 1982).

The phyllophotometric efficacy (K'_{ps}) is simply given by the ratio between the phyllophotometric flux and in phytons and power in watts and the unit is phyton per watt (pt W^{-1}),

$$K'_{ps} = \frac{\phi_{ps}}{\phi_e} \tag{16}$$

The quantity for phyllophotometric energy (Q_{ps}) is given by the integral of ϕ_{ps} over a given time duration (Δt) and unit is phyton second (pt s).

$$\mathrm{Q}_{ps} = \int_{\Delta t} \phi_{ps} dt \tag{17}$$

The phyllophotometric intensity (I_{ps}) of a source in a given direction is given by the quotient of the photosynthetic photon flux ($d\phi_{ps}$) leaving the source and propagating in the solid angle $d\Omega$. Its unit is phyton per steradian (pt sr^{-1}).

$$I_{ps} = \frac{d\phi_{ps}}{d\Omega} \qquad (17)$$

The phyllophotometric radiance (L_{ph}) in a given direction, at a given point of a real or imaginary surface is defined by the following expression,

$$L_{ps} = \frac{d\phi_{ps}}{dA \cos\theta d\Omega} \tag{18}$$

where $d\phi_{ps}$ is the phyllophotometric flux transmitted by an elementary beam passing through the given point and propagating in the solid angle $d\Omega$ in the given direction. dA is the area of a section of that beam including the given point. θ is the angle between the normal to that section and the direction of the beam. The unit of L_{ps} is phyton per steradian per square meter (pt sr^{-1} m^{-2}).

Phyllophotometric irradiance at a point of a surface (E_{ps}) is given by the phyllophotometric flux $d\phi_{ps}$ incident on an element of the surface containing the point, by the area dA of that element. The unit of E_{ps} is phyton per square meter (pt m^{-2}).

$$E_{ps} = \frac{d\phi_{ps}}{dA} \tag{19}$$

The phyllophotometric exitance (M_{ps}) at a point of a surface is given by the quotient of the phyllophotometric flux $d\phi_{ps}$ leaving an element of the surface containing the point, by the area dA of that element. The unit of M_{ps} is phyton per square meter (pt m^{-2}).

$$M_{ps} = \frac{d\phi_{ps}}{dA} \tag{20}$$

3.4 Results

An important aspect in horticultural lighting is the energy performance of the light sources used. The efficacy values give an indication to a certain extent about the energy performance of such radiation source. Figure 22 compares the relative radiometric, quantum, phytometric, phyllophotometric and photometric efficacy potentials of different light sources. It can be verified that there is no direct correlation between the efficacy potential values given by the different measurement systems for the light sources under evaluation. An important observation is however, that the spectrally tailored LED light source composed of red and blue LEDs (RB-SSL) with peak wavelengths at 640 nm and 460 nm, respectively, has the highest energy saving potential according to all measurement systems, with the exception of the photometric system. If the material physics limitations of the light sources are taken into account this would further benefit the RB-SSL light source in relation to conventional light sources such HPS lamps. Although most of the commercially available high-power LEDs have nowadays an electrical efficiency of above 20%, their potential efficiency is far better. Internal quantum efficiency measures the percentage of photons generated by each electron injected into the active region. In fact, the best AlInGaP red and AlInGaN green and blue LEDs can have internal quantum efficiencies of almost 100% and 50%, respectively (Steigerwald et al. 2002).

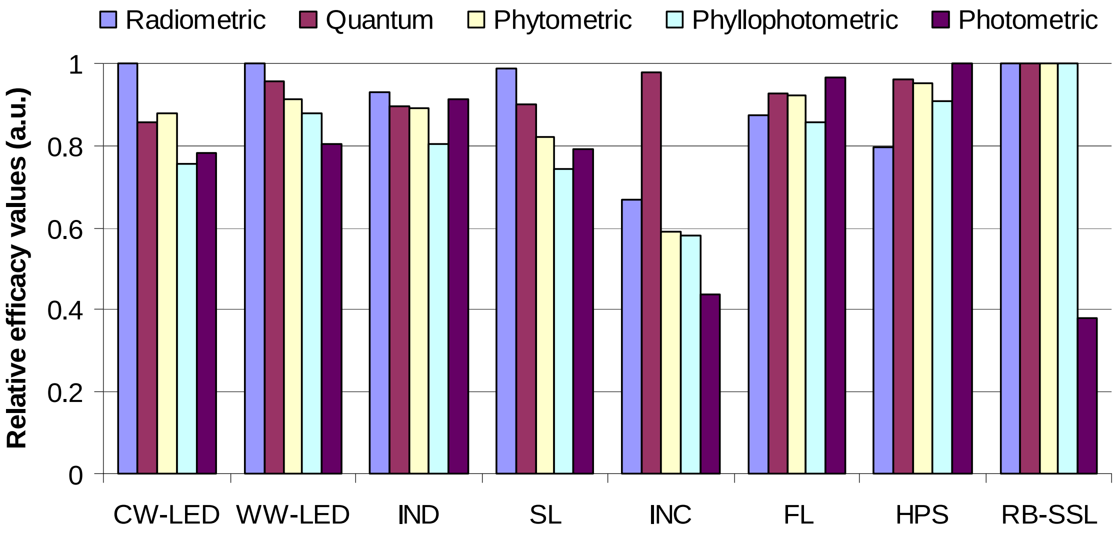


Figure 22 - Comparison of relative efficacy potential of cool-white phosphor converted LED (CW-LED), warm-white LED (WW-LED), induction lamp (IND), sulfur lamp (SL), incandescent lamp (INC), fluorescent lamp (FL), high-pressure sodium lamp (HPS) and red and blue LED (RB-SSL) light sources defined by different radiation measurement systems.

Also using the efficacy values obtained according to the different measurement systems, it is possible to evaluate the spectral energy saving potential (SESP) of one light source relative to another. The SESP represents in this case the minimum attainable gain in electrical efficiency due only to the spectral composition of the light source.

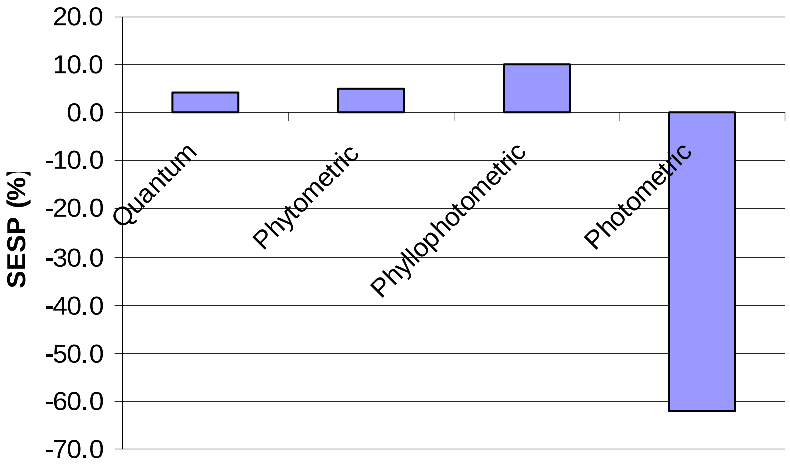


Figure 23 - Spectral energy saving potential (SESP) of the RB-SSL relatively to HPS radiation evaluated by different measurement systems.

Figure 23 shows the results obtained for the SESP of the RB-SSL relative to HPS radiation, evaluated by the quantum, phytometric, phyllophotometric and photometric systems. It can be seen that the

SESP given by the photometric system is negative, representing a negative gain in terms of energy saving. This result comes in agreement with the fact that the light source composed by a mixture of red and blue light is not optimal for vision. The photometric system favors light sources which have their spectrum within the $V(\lambda)$ response curve, such as that of HPS lamps. Another interesting fact is that the phyllophotometric SESP for the RB-SSL light source is two times higher than the ones given by the quantum and phytometric units.

However the SESP only indicates the contribution of the light source spectrum to the overall energy savings potential of a real luminaire system. To evaluate the overall energy saving potential of a luminaire the losses on optics, drivers and lamps must be considered. A wider evaluation takes also into account the economic aspects of utilization of luminaires. In order to evaluate and quantify these aspects, considering simultaneously the photosynthetic response curve of the plants, a comparative study is here made between a conventional 400-W HPS luminaire and an equivalent (i.e., same phyllophotometric flux) RB-SSL LED luminaire composed of red and blue LEDs with peak wavelength emissions at 640 nm and 460 nm, respectively. The normalized spectral photon distributions of these sources are shown in Figure 24 with the relative photosynthetic quantum efficiency curve of the plants (RQE).

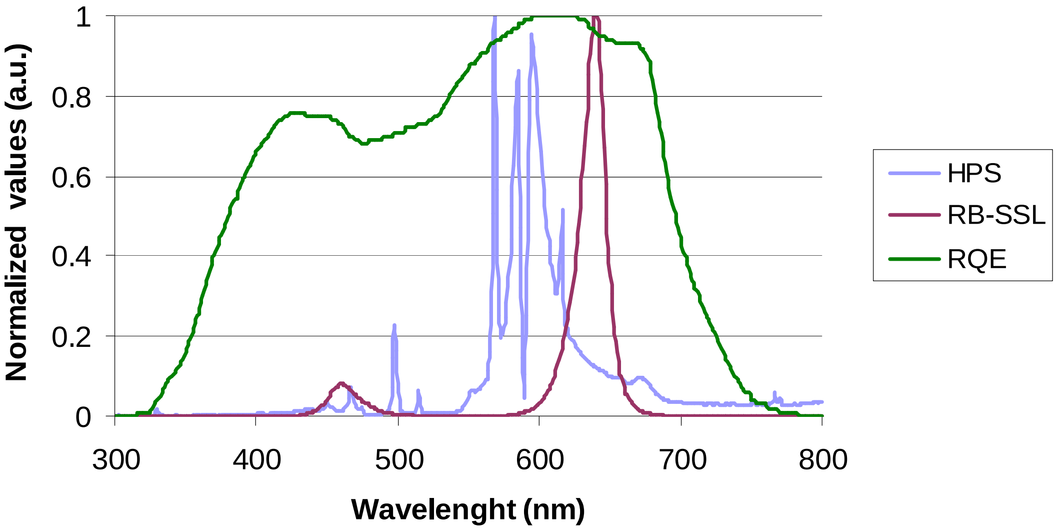


Figure 24 - Normalized spectral photon flux distribution of conventional high-pressure sodium lamp (HPS) and a LED luminaire composed by red and blue LEDs (RB-SSL) and the mean photosynthetic relative quantum efficiency curve (RQE).

Table 4 estimates the light costs of high-pressure sodium and LED lamp composed of red and blue LEDs with equal phyllophotometric flux output. The estimation is based on typical electro-optical parameters of the lamps in real operation conditions. A depreciation of 40% in the light output relative to the initial value given by the manufacturer was used for the LEDs, considering their typical thermal performance. This level of depreciation value is typical in LED-based luminaires using common and low-cost passive cooling solutions. The lifetime of power LEDs is commonly defined at 70% or 50% lumen maintenance. However, for plant-growth applications, it is economically preferable and recommended by lamp manufactures that the replacement of high-pressure sodium lamps should occur between 85% and 90% of the initial lumen output. For high-pressure sodium lamps this is equivalent to approximately 10000 hours of operation, while, for high-brightness red and blue LEDs, 30000 hours or higher can be reached. The total phyllophotometric flux of the high-pressure sodium luminaire was obtained considering 60% luminaire efficiency due to losses in the optical elements. For the LED luminaire, 90% was used. Besides the losses on the optical elements of the luminaires, the phyllophotometric efficacy value also takes into account the overall system losses, including the light sources and drivers.

Table 4 - Comparison of photosynthetic radiation costs between HPS and RB-SSL light sources considering real plant growth operation conditions.

	HPS	**RB-SSL**
Phyllophotometric efficacy [μpt/W]	91,7	87,3
Lifetime [h]	10 000	30 000
Phyllophotometric flux [mpt/luminaire]	38	38
Input power [W/luminaire]	414	435
Lamp cost [€/mpt]	685	23711
Lamp cost [€/lamp]	26	900
Capital cost [€/pt·h]	0,070	0,791
Operating cost [€/pt·h]	0,872	0,917
Ownership cost [€/pt·h]	0,942	1,708

The ownership cost results from the sum of operating costs and capital investment costs (Rea 2000). The results show that one of the aspects delaying the uptake of LED technology in horticultural lighting is the high capital cost, which is more than 10 times higher for LEDs than for high-pressure sodium lamps. This is mainly due to the high initial investment costs, especially in purchasing of LEDs. The operating costs of the red and blue LED luminaire are almost the same as those of the high-pressure sodium luminaire, due to the similar efficiency or phyllophotometric efficacy values.

Due to the high capital cost the resultant ownership cost for the LED lamp is almost 2 times higher than for the HPS lamp. Operating the LEDs at junction temperatures of 25°C under normal conditions would reduce the ownership cost of the RB LED in 20% in relation to the previous value. In spite of the higher phyllophotometric efficacy of approximately 140 μpt W^{-1}, obtained at operating at this low junction temperature the lamp would continue to have a higher ownership cost in comparison to the HPS lamp. However, due to the fast technological development of LED technology, the light output per device is increasing and the costs are decreasing. According to the Haitz's law, the evolution of performance of red LEDs in terms of radiation output has been increasing by a factor of 20 per decade, while the cost is decreasing by a factor of 10 (Bergh et al. 2001). At this pace, it is expected that the ownership costs of a similar type of red and blue LED luminaire will be similar to the ownership costs of conventional high-pressure sodium luminaries by the year of 2010.

3.5 Discussion and conclusions

The establishment of a measurement system to quantify radiation in plant growth will allow a more appropriate design, characterization and optimization of future lighting installations for plant growth. Also, with respect to the economics of this, it is expected that a coherent metrology will better forecast and correlate investments in lighting with the expected and desirable benefits.

If the photosynthetic capability of a light source is to be quantified, then the nature of its actinic response should also be considered. By weighting the spectral power distribution of the light source with the relative quantum efficiency curve, the phytometric system overestimates the influence of the red photons contribution to photosynthesis, while underestimates the contribution of blue photons. This aspect is corrected in the phyllophotometric system, which uses the spectral photon flux distribution of the light source and the relative quantum efficiency curve as the basis for its development. The development of CCD-based high-resolution portable spectroradiometers will make the implementations of phyllophotometer devices a straightforward process and a useful tool for growers in the horticulture crop industry. Additionally, it brings accuracy and flexibility to photosynthetic radiation measurements in plant growth.

Although the quantification of radiation may be straightforward, its characterization and qualification has to be addressed carefully. The utilization of just one parameter to characterize the photosynthetic performance of a light source for plant growth might not be sufficient. Similarly in photometry, the luminous efficacy does not characterize the quality of a light source for vision. In photometry, additional parameters, such as colour rendering index and correlated colour temperature are used.

Perhaps additional quantities may be developed to evaluate the characteristics of a light source regarding its overall plant-growth performance. As is the case with the physiological and morphological effects of different wavelengths on plants, the values of photosynthetic efficacies or efficiencies are not necessarily addictive. Perhaps additional parameters such photomorgenesis, phototropic or flowering index could also be used to characterize the appetence of a light source for plant growth. Just as with luminous efficacy, phyllophotometric efficacy values do not fully characterize the overall electrical energy efficiency of the light source. However, it can be used as an indicator in combination with photomorgenesis and phototropic indexes to have an overall indicator value that can effectively and more clearly characterize the radiation quality for a specific cultivar.

The development of a coherent metric system is not only important for the photobiological aspects ruling the year-round horticultural crop production, but also for the economic aspects. Reducing the capital cost is the key issue to successful economic implementation of LED luminaires as supplemental light sources in year-round horticulture. The fast developments of LED technology and cost reductions are indispensable factors for the uptake of solid-state lighting by the horticultural industry. This will allow the development of solid-state lighting systems without sophisticated and complicated technical solutions reinforcing the technical and economical viability. It is worth keeping in mind that the final output in year-round horticultural crop production is not measureable in terms of watts, lumens, phytowatts, photons or phytons. Therefore, a more complete financial analysis to address the benefits of retrofitting existing conventional lighting systems by LED-based systems should also involve the final benefits in crop productivity, production cycle, efficiency gains and final sale value resultant from the radiation used. Nevertheless, the economics of future solid-state lighting installations for year-round crop production are attractive and promising as long as the LED technology continues to mature and costs continue to decrease.

The best way to measure radiation in plant-growth applications is to improve the measurement accuracy, address the interoperability between the existing measurement systems and thereby serve as a useful tool in comparing light sources for plant-growth applications. In spite of the fact that the photopic spectral response curve of the human eye $V(\lambda)$ was proposed in 1924 and later used as the basis of all photometric measurements, its standardization only occurred almost 80 years later in 2004 (CIE 2004). It is hoped that the evaluation procedure and standardization of the metrics for photosynthetic radiation will be completed in a more straightforward manner and within a shorter time.

4 Discussion and conclusions

During the reported growth test in greenhouse conditions AlInGaN and AlInGaP LED-based luminaries have been developed and its effects on lettuce growth were evaluated. In comparative growth tests the influence of spectral composition of the light treatments should be evaluated under the same abiotic conditions. Therefore, growth chambers, growth rooms or phytotrons are commonly employed in order to properly control the growth conditions and avoid other external interferences. However the goal of the reported growth test was to find out the effects of the spectral composition of the light emitted by the LEDs when they are used as supplemental light to daylight. However, in greenhouse conditions the accomplishment of such type of experiments is more complex. In order to effectively compare the results obtained in result of each light treatment a few conditions have to be assured. One of the conditions is to maintain the same daylight contribution to the total PPF provided in each supplemental light treatment equal. This will guarantee that the daily light integral remains similar for the light treatments under investigation throughout the whole test duration. However such experiment would require experimental set-ups with light sources with the same dimension, form, light spatial distribution and light output.

The ambient temperature is another important abiotic parameter, which was difficult to maintain equal in all growth areas during the growth test. Although the power dissipation of the LED and HPS systems were approximately the same and in spite of the LEDs luminaires were installed three time closer to the plants than HPS lamps, the temperature of the growth areas lit by LEDs were the lowest. The higher temperature verified at HPS growth areas was due to the high infra-red emission of the HPS lamps in comparison with the LED luminaires which do not emitted in this spectral region.

The possibility of using LED luminaires close to the plants without hinder its development may be another advantage of solid-state lighting in relation to conventional lighting such as HPS lighting. The appropriated thermal management of the LED luminaires has shown to be indispensable to guaranty the reliability and the optical performance of the system. Lowering the operation junction temperature of the LEDs enhance the optical and thermal performance of the luminaries by maintaining the optical emission and life expectancy as high as possible. However, the heat losses generated due to lighting in greenhouses might not be totally misused. In countries located at northern latitudes such as Finland, greenhouses need to be heated during the winter period when coincidentally also supplemental artificial lighting is required. The 70% to 80% of heat losses resulted from the normal operation of LEDs can be used to heat-up greenhouse during the winter, although there are other forms of heating which are more costly effective than electrical heating.

Another aspect involved in comparative growth tests is related to proper evaluation, comparison and quantification of the radiation used in the light treatments. A few attempts have been carried out to establish a universally accepted and used metrics to photosynthetic radiation. The PAR metrics is the most commonly used, however it does not take into account the relative photosynthetic spectral response curve of the averaging plant. To proper evaluate the effects on plant growth resulted from the use of different light treatments, is indispensable to quantify the photosynthetic radiation as exactly and as coherently as possible. Therefore the phyllophotometric system here presented intends to contribute towards this final goal by trying to propose a systematic basis for units and nomenclature for quantification of photosynthetic radiation. However, photosynthesis is just of the process related with the interaction of plants with light. Photosynthesis is the main and perhaps the most important process related with the interaction of plants with light. However there are others light-dependent processes such as photomorphogenesis and phototropism. Future work will be used to further develop, test and evaluate the presented system.

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