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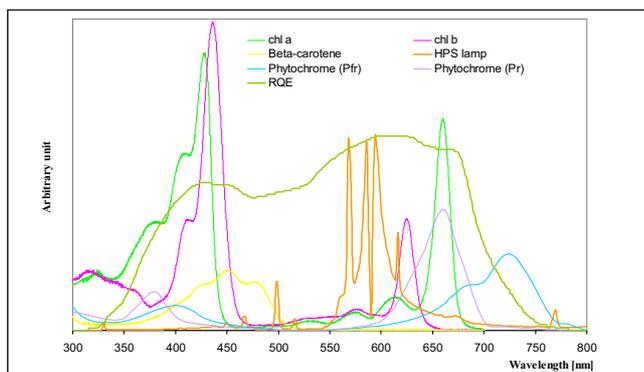
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Design and Performance Assessments of Solid State Light Sources for Plant Growth

Paulo Pinho, Eino Tetri, Liisa Halonen

1. Introduction

The light emitting diode (LED) has been broadly used in many areas spread throughout a wide range of applications. In horticulture, LEDs have also gained importance due to their well known physical, electrical and optical characteristics. Their continuous technological development has been reinforcing the utility of using them as an artificial light source for plant growth. The main advantage resides on their spectral emission characteristic. This has been a decisive factor for the increasing research work that has been done in the development of LED luminaires for plant growth applications. Nowadays HPS (high pressure sodium) lamps have been the preferred light sources for many types of crops in horticulture industry. Their electrical efficiency (i.e., ratio between the electrical input power and the radiant output power inside the visible range) which is around 30%, together with low price, long life time and high radiant power per lamp has been the main reasons for their dominance. Nevertheless their spectral output is not the most appropriated one to promote photosynthesis and for the morphology of the plants. This results that plants grown under HPS have shown excessive leaf and stem elongation [1], [2]. The main cause is due to the unbalanced spectral emission of HPS lamps in relation to the main absorption peaks of important photosynthetic pigments such as chlorophylls- a (chl a) and b (chl b), beta-carotene and phytochromes (Pfr and Pr) as shown in Pic.1. This results also that the radiant energy utilization is not the ideal one considering the plant's average response curve represented by the relative quantum efficiency (RQE) curve. The RQE measures the rate of carbon dioxide uptaken per unit rate of absorption of quanta and is based in normalized mean values in analogy with the sensitivity curve of the human eye [3], [4].



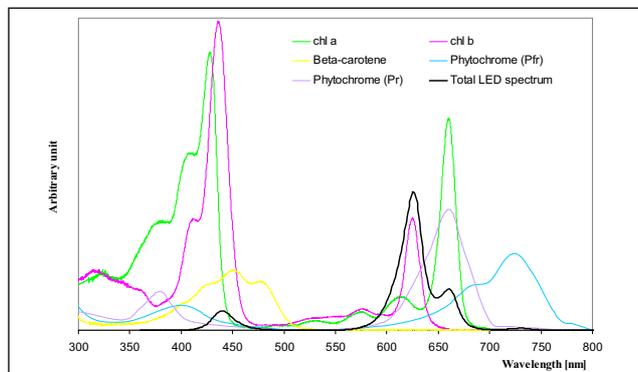
Pic.1 – Comparison of the spectral emission of HPS lamps with the absorption spectra of photosynthetic pigments and the plant's response curve (RQE).

The advent of solid state lighting has made possible to control more efficiently and effectively the spectrum of light which is provided to the plant. In such way the main physiologic aspects of the plant can be better regulated

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and controlled throughout the quality of light provided. In addition to better photosynthetic rates and improved photomorphogenesis can also be achieved.

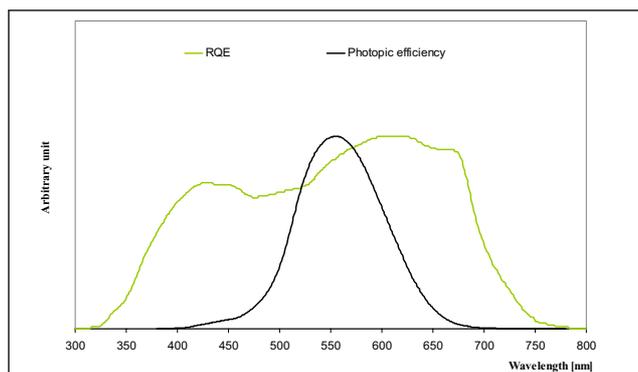
To maximize crop productivity together with an efficient use of electrical energy the light spectrum is intended to match with the most important absorption peaks of the photosynthetic pigments. LEDs can fulfill this important requirement due to their narrow-band spectral emission characteristic as shown in Pic.2.



Pic.2 – Matching between the spectral emissions of a multi-wavelength LED luminaire and the absorption peaks of photosynthetic pigments.

2. Metrics in Lighting for Plants

Designing a LED luminaire for plant growth involves also the knowledge of metrics used to measure light for plants. Photosynthesis and photomorphogenesis are two of the physiologic processes occurring on the plant related with light acquisition. Photomorphogenesis is related with structural development of the plant resulting from the spectral quality of the light provided. Some photomorphogenetic responses are the germination, stem extension, leaf expansion, root growth, phototropism. These responses are mediated by different groups of blue/UV-A photoreceptors. Photosynthesis is directly related with light interaction throughout the photoreceptors in the chloroplasts' thylakoid membranes located in the leaves' mesophyll cells. Plants use photosynthesis to convert the radiant energy of the light into chemical energy to be used by molecules for production of biomass. Photosynthesis is driven by the number of photons falling on the plant's leaves per second. Therefore the most commonly found units to measure light for plants are based on the photon system of measurement. Plants have different spectral response to light than humans as it can be seen by comparison of the two response curves shown in Pic.3. Those differences justify in part why light sources that have shown good performance for vision, might be not so effective for plant growth applications.



Pic.3 – Comparison of the plant's response curve (RQE curve) and human eye response at photopic conditions (photopic efficiency curve).

The mean photosynthetic quantum yield of the plants or RQE curve is comprised between 300 and 800 nm [5], although nowadays the spectral region comprised between 400 and 700 nm has been used to measure light for plants. This region is commonly called as photosynthetically active radiation (PAR) region [6]. Most of the quantum sensors for plant applications use PAR to measure the photosynthetic photon flux (PPF). The yield photon flux (YPF) is another method to measure PAR which now takes into account the RQE curve. Both PPF and YPF are commonly given in $\mu\text{molm}^{-2}\text{s}^{-1}$ where 1 mole stands for 6×10^{23} photons and 1 μmole for 6×10^{17} photons. As the name indicates “*quantum sensors*”, are based on the photon measurement system and therefore their spectral response is different from the plant’s response curve. Desirable would be to have a system to measure light for plants which could take into account the RQE curve in analogy with the photometric system for the sake of coherency, accuracy, interoperability and interchangeability between the different light measurement systems.

In some situations PPF can also be measured in Wm^{-2} by using an irradiance meter. This type of measurement is based on the radiometric measurement system, and can be easily converted into photon measurement system units. Eq.1 shows how the PPF in Wm^{-2} can be converted into $\text{molm}^{-2}\text{s}^{-1}$ and vice-versa using spectral irradiance data. PPF is represented by E_p in $\text{molm}^{-2}\text{s}^{-1}$, and can be obtained by the integration between 400 and 700 nm of the spectral irradiance $E_{e,\lambda}$ in $\text{Wm}^{-2}\text{nm}^{-1}$ multiplied by the spectral conversion factor which is determined by the ratio between the wavelength λ in meters and the Avogadro’s number N ($6,02 \times 10^{23}$), the Planck’s constant h ($6,63 \times 10^{-34}$ J s) and the velocity of light c ($3,00 \times 10^8$ m s^{-1}).

$$E_p = \int_{\lambda=400\text{nm}}^{700\text{nm}} \left(\frac{\lambda}{N \times h \times c} E_e(\lambda) \right) d\lambda \cong \sum_{\lambda=400\text{nm}}^{700\text{nm}} \frac{\lambda}{N \times h \times c} E_{e,\lambda} \quad (1)$$

When spectral values are not available, an approximation can be done using the peak wavelength of the LED (λ_{peak}) as represented by Eq.2.

$$E_p = \frac{\lambda_{\text{peak}}}{N \times h \times c} E_e \quad (2)$$

3. Photosynthetic LEDs

Photosynthesis and photomorphogenesis processes have chlorophylls, carotenoids and phytochromes as the main photopigments. They have their own characteristic spectral absorption with important localized peaks that are intended to be matched by the spectral emission of the LEDs. Today’s state-of-art LEDs based on indium gallium nitride (InGaN) technology are available from ultraviolet (UV) into the green region of the visible spectrum. Those devices are important for plant growth because they can emit in the blue/UV-A region where carotenoids have their absorption peaks located. Blue/UV-A photopigments mediate important morphological responses such as endogenous rhythms, organ orientation, stem elongation and stomatal opening.

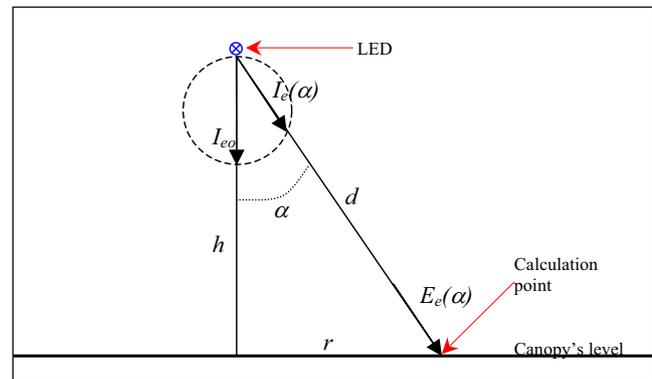
Chlorophyll-a has a strong light absorption peak located around 660 nm. High-power aluminum gallium arsenide (AlGaAs) LEDs emit in the same region but due in part to the low market demand and old technology of production they are extremely expensive devices compared with phosphide- or even nitride-based materials. AlGaAs LEDs can be also used to control phytochromes, which mediate important morphological responses such as germination, stem extension and leaf expansion. The two interconvertible isomeric forms of phytochromes have their absorption maxima at 660 nm and 730 nm. Nowadays, high power aluminium

gallium indium phosphide (AlInGaP) LEDs are based on a well-established material technology with the highest optical and electrical performance in the visible spectrum. AlInGaP red LEDs can emit near to the absorption maxima of chlorophyll b (chl b) around 625 nm, and therefore are also useful to promote photosynthesis.

With exception of AlGaAs LEDs the market acceptance for all other considered photosynthetic LEDs has been good and due to that the production costs have been decreasing as well as prices. Nevertheless, their electrical and optical performance is not yet high enough in order to compete with HPS lamps as the main artificial light source for plant growth. Nowadays one 400-W HPS lamp can produce approximately 120 Watts of PAR with an electrical efficiency which can reach 30%. According to measured results 1-W blue LEDs can convert around 20% of its input power into radiant power while 1-W red approximately 19%. While the luminous output of the LEDs has been following the Haitz’s law, doubling every 18-24 months [7], the luminous efficacy has been marked by a slower pace. Based on the forecast of the luminous efficacy of LEDs for the coming years [8] it is expected that the efficiency of energy conversion of LEDs will overcome the one of HPS lamp by the year of 2009. Nevertheless due to the fast technological advancements and constant breakthroughs this situation might be achieved even sooner.

4. PPF Distribution on the Plant’s Canopy

The PPF level at plant’s canopy is determined considering the individual contribution of LEDs which compose the array. The individual contribution of each LED on the total PPF level is determined using the inverse square law, considering the LED as a point source. Pic.4 shows the schematic diagram representing the dimensions involved in the calculation of the PPF at a certain point on the horizontal plane defined at the plant’s canopy level at a distance d from the LED.



Pic.4 – Schematic representation of the dimensions involved in the calculation of the PPF at a certain point on the horizontal plane defined at the plant’s canopy level.

For a perfect Lambertian LED emitter the spatial distribution of the radiant intensity is given in Eq.3, where I_e is the radiant intensity of the LED at an angle α defined by the calculation point location and I_{e0} is the radiant intensity in a direction perpendicular to the horizontal plane and below the LED.

$$I_e(\alpha) = I_{e0} \times \cos \alpha \quad (3)$$

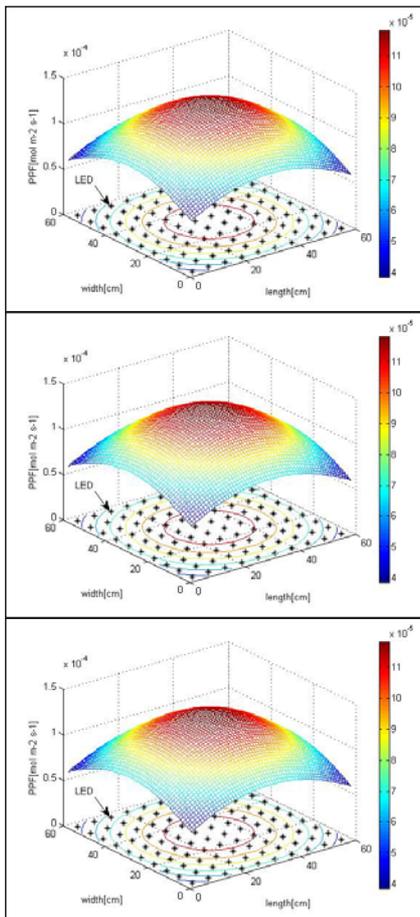
By applying the inverse square law it is possible to obtain the expression which calculates the irradiance level at the calculation point. This expression is given by the Eq.4.

$$E_e(\alpha) = \frac{I_{e0}}{d^2} \times \cos \alpha \quad (4)$$

Eq.5 gives the final expression for calculation of the PPF.

$$E_p(\alpha) = \frac{\lambda_{peak} \times I_{eo}}{0,1197 \times d^2} \times \cos \alpha \quad (5)$$

As it happens in most of lighting applications the uniformity of the light distribution over the surface should be as good as possible. LEDs have half-isotropic emission which makes them directional emitters. Nevertheless some of the emitted photons propagate in directions defined by large dispersion angles. Depending on the mounting height this results that in certain situations a significant portion of the light emitted is misused. For those cases the radiation pattern of the light emitted by the LED should be more carefully considered. The use of secondary optics or LEDs with small viewing angle can be a valid option in order to more efficiently direct the light towards the area to be illuminated. Collimator lens are not perfect devices although they have a high optical coupling efficiency which can be up to 85 or even 90% in some cases. Collimators are encapsulating lens which can reduce the number of LEDs required to achieve the desirable PPF level and therefore reduce the wiring complexity. Pic.5 shows the influence of collimating lenses of different dispersion angles on the PPF distribution. In the first figure Lambertian emitters with a 120° total viewing angle, where used without secondary optics. The middle one shows the influence when 60°-collimators lenses were used with the LEDs. The last figure shows the results using 10°-collimators lenses on the LEDs. For comparison purpose the mounting height, the illuminated area and the average PPF (100 μmolm⁻²s⁻¹) were maintained constant. In these computer simulations the collimators were considered to have an optical efficiency of 90%. The LEDs used on the simulation was modeled based on a 3,9-cd Lambertian emitter with total luminous flux of 12 lm and peak emission at 461 nm. The LED array is located at 30 cm above the horizontal plane defined by the plant's canopy. The area illuminated has a square form with 60-cm side.



Pic.5 – Influence of collimating lenses on the PPF distribution.

Collimating lenses	Without	60°	30°
Number of LEDs	90	52	42
Uniformity (%)	59,9	43,4	37,6
PPF _{ave} (μmolm ⁻² s ⁻¹)	100	98	100

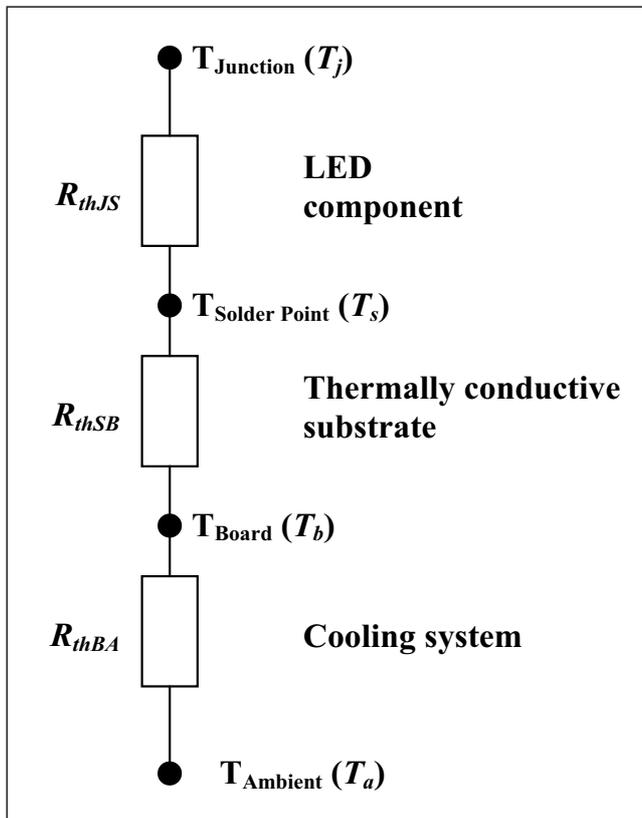
Char.1 – Resume of the computer simulations results obtained on the influence of collimating optics on the PPF distribution.

The results of the simulations indicate that reductions of the number of LEDs can be achieved by collimating the light emitted with some expense on uniformity. The uniformity is given by the ratio in percentage between the minimum PPF and the average PPF (PPF_{ave}) on the calculation surface. A resume table of the simulation results is given in Char.1. In situations where uniformity is an important factor, there are commercially available LEDs with batwing radiation pattern which results in a more uniform distribution of the radiation on a horizontal plane than Lambertian emitters. Ultimately, the use of collimating lens can helpful to increase the mounting height of the luminaire maintaining the same number of LEDs without reduce the average level of the PPF.

5. Thermal Management

LEDs are still nowadays to be referred as potentially efficient devices. This means that the expected high electrical efficiency goal was not yet achieved. Nevertheless continuous technological breakthroughs have made LEDs around two times more efficient in producing visible light than incandescent lamps. While incandescent lamps can only convert 5 to 10% of its input power into visible radiation, LEDs can produce more than 20%. The best reported electrical efficiencies were around 45 and 25% for AlInGaP and AlInGaN system alloys, respectively (7). Although the internal quantum efficiency of some LED emitters can approach almost 100% (8) the extraction of the generated photons to the exterior of the device still face some difficulties. Most of the photons generated in the active region are absorbed inside the device. The internal resistance of the semiconductor material generates heat losses which need to be conducted to the exterior throughout a small slug. The thermal management of high-power LEDs is difficult because the removal of heat from inside the device rely primary on natural convection. In order to reduce the thermal resistance of the heat path from the junction to the exterior, an external heat sink need to be added to most of the high-power LEDs. The heat sink will allow that the junction temperature doesn't overcome the maximum allowable temperature defined by the manufacturer. Maintaining the junction temperature within acceptable limits allows a reliable operation of the device avoiding premature failure. The operation life time is one of the advantages of the LEDs over other conventional light sources. To maintain the long life time of the LEDs is desirable to have a good thermal management of the LED luminaire.

In general the data provided in the manufacturer's datasheet is usually referred to operation with a junction temperature of 25°C. In most of the applications operation at this junction temperature is not possible. In great majority of the applications the junction temperature will be higher than 25°C. This will represent a decrease on light output making the thermal design very important and indispensable. Therefore the maximum ambient temperature expected in the operation environment should be used to determine the thermal resistance of the heat sink to be added to the LED. In Pic.6 is shown the simplified equivalent thermal circuit of an LED placed on a thermally conductive substrate with the required cooling system.



Pic.6 – Simplified thermal circuit of an LED placed on an external heat sink throughout a thermally conductive substrate.

Using Eq.6 and Eq.7 is possible to determine the thermal resistance (R_{thBA}) of the external heat sink required to maintain the junction temperature below the maximum value specified by the manufacturer. For that the values of the total power dissipation (P_D) of the LED, the thermal resistance from junction to solder point thermal (R_{thJS}) and the substrate thermal resistance (R_{thSB}) need to be known from the manufacturer's datasheets.

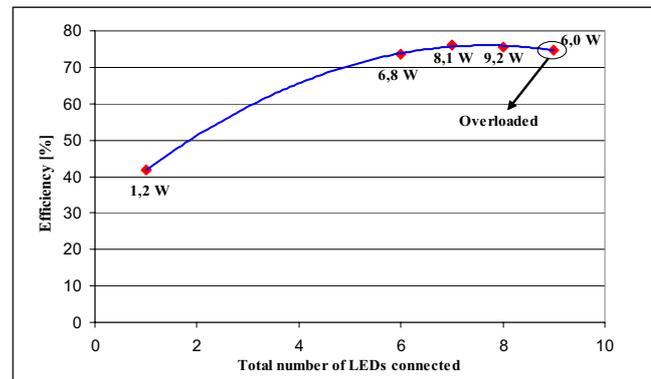
$$R_{thJA} = \frac{T_j - T_a}{P_D} \quad (6)$$

$$R_{thBA} = R_{thJA} - (R_{thJS} + R_{thSB}) \quad (7)$$

6. Performance Evaluation

The general evaluation of an LED luminaire for plant growth applications can be done in terms of its electrical and photosynthetic performance. The electrical performance can be evaluated by the electrical efficiency. The overall electrical efficiency is given by the ratio of the input power and the radiant output power inside the PAR region. The efficiency of the electronic drivers is desirable to be as high as possible to maintain optimal the overall efficiency of the LED luminaire. Nowadays constant current LED drivers have efficiencies ranging between 70 to 95% depending on their output power ratings and circuit topologies. Switched-mode constant current drivers have the advantage of eliminate the need of wasteful limiting resistors on the LED arrays simplifying the design process. Moreover they easily allow dimming control features by using pulse width modulation (PWM). Pic.7 shows the tendency curve of the electrical efficiency of a commercial available constant current switched-mode operated LED driver. The curve is based on measurements at different operation points. This driver can only provide a maximum output power of 10 W and has overload protection feature. For each point the efficiency, the output power of the LED driver and the number of 1,2-W

LEDs connected are given. The figure shows a typically efficiency curve which is common to most of the commercially available LED drivers. The efficiency curve shows that it is recommended to maintain the operation point close to the nominal power in order to maintain a good electrical performance of the driver.



Pic.7 – Typical tendency curve of the electrical efficiency of a commercial available 10-W LED driver.

The photosynthetic performance can be evaluated considering two aspects. The first one is the photosynthetic utilization efficiency (PUE), which depends on the spectral emission of light source and can be compared to the luminous efficiency in the photometric system. The PUE is given by the ratio between the PPF and the YPF and represents how efficiently the radiant energy is converted into chemical energy. The second aspect is the net assimilation rate (NAR) which mostly dependent on the photosynthetic rate and photomorphogenesis. To determine NAR is necessary to measure the mean leaf area (LA_1 and LA_2) and the dry mass (W_1 and W_2) of the plants at different times (t_1 and t_2) during the period of growth. Eq.8 represents the mathematical expression for calculation of NAR [10].

$$NAR = \frac{(\overline{W_2} - \overline{W_1}) (\ln \overline{LA_2} - \ln \overline{LA_1})}{(t_2 - t_1) (\overline{LA_2} - \overline{LA_1})} \quad (8)$$

The combination of PUE and NAR leads us to the concept of photosynthetic efficiency. Photosynthetic efficiency can be literally described as the ability of the light source in providing an appropriated spectral radiation which could ultimately enhance not only the photosynthesis rate but also the photomorphogenesis of the plant. In resume the best light source would then be the one who could present the greatest product between the electrical conversion efficiency, the PUE, and the NAR.

7. Conclusions

During the design stage of an LED luminaire for plant applications several compromises need to be established. The design of an LED-based luminaire for plant growth has to have into account the maximum photosynthetic and photomorphogenesis performance of the plant. This should be achieved with the maximum energy efficiency possible. Due to the high cost of LEDs and wiring complexity the number of emitters required should be reduced to the minimum indispensable number. The use of secondary optics, namely collimators can reduce the number of LEDs required to achieve a certain PPF light level. This is achieved by redirecting more effectively the light beam to where it is required and reducing in that way the light waste. Due to reduction on the number of LEDs the required input power is less resulting in lower running time costs. Depending on the type of optics used and their optical efficiency and commercial price reduction on the initial costs of the luminaire can be

attained. The initial costs include electronic drivers, LEDs and secondary optics. Nevertheless a trade-off between mounting height of the luminaire, costs, circuitry simplification and lit uniformity is required considering the specific lighting strategy and the application itself.

By using LED luminaires plants can be lit in different and more flexible ways than ever before. Small luminaires may be design in order to allow a distributed lighting strategy closer to the plants which makes the illumination more effective. The use of LEDs as an artificial light source in horticulture sounds promising. The high potential of energy conversion, small size, directional light, spectral emission and chromaticity variety will make LEDs a viable light source in artificial lighting for plants in the future. Until then, prices reductions and increments on the total radiant output power per device have to continue. Just in that way will be possible that LED-based luminaires for plant growth compete with conventional and low cost light sources such as HPS lamps, in a more effective way.

References

- [1] Tibbitts, T. W., Morgan, D. C., and Warrington, I. J., 1983. "Growth of lettuce, spinach, mustard, and wheat plants under four combinations of high-pressure sodium, metal halide, and tungsten halogen lamps at equal PPFD", *Journal of the American Society for Horticultural Science*, 108, pp. 622-630.
- [2] Wheeler, R. M., Mackowiak, C. L., Sager, J. C., "Soybean stem growth under high-pressure sodium with supplemental blue lighting", 1991, *Agronomy journal*, v. 83 (5): 903-906.
- [3] McCree, K. J., 1972a, "The action spectrum, absorptance and quantum yield of photosynthesis in crop plants", *Agricultural and Meteorology*, vol. 9, pp. 191-216.
- [4] McCree, K. J., 1972b, "Test of current definitions of photosynthetically active radiation against leaf photosynthesis data", *Agricultural and Meteorology*, vol. 10, pp. 443-453.
- [5] Sager, J. C., Edwards, J. L., Klein, W. H., 1982, "Light energy utilization efficiency for photosynthesis.", *Transactions of the ASAE - American Society of Agricultural Engineers*, vol. 25(6), p. 1737-1746.
- [6] CIE Publication 106, "Terminology for photosynthetic active radiation for plants", 1993, pp. 42-46.
- [7] Krames, M. R.; Amano, H.; Brown, J. J.; Heremans, P. L.; 2002 - Introduction to the issue on high-efficiency light-emitting diodes, *Selected Topics in Quantum Electronics IEEE Journal*, vol. 8(2), pp. 185-188.
- [8] Steigerwald, D.A.; Bhat, J.C.; Collins, D.; Fletcher, R.M.; Holcomb, M.O.; Ludowise, M.J.; Martin, P.S.; Rudaz, S.L.; (2002), "Illumination with solid state lighting technology", *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 8(2), March-April 2002, pp. 310-320.
- [9] Tsao, J. Y., 2003, "Roadmap projects significant LED penetration of lighting market by 2010", *Laser Focus World*, May 2003.
- [10] Sager, J. C., Smith, W. O., Edwards J. L., Cyr, K. L., 1988, "Photosynthetic efficiency and phytochrome photoequilibria determination using spectral data", *Transactions of the American Society of Agricultural Engineers*, vol. 31 (6), pp. 1882-1889.