Helsinki University of Technology
Department of Electronics, Lighting Unit
Espoo 2008 Report 49

USAGE AND CONTROL OF SOLID-STATE LIGHTING FOR PLANT GROWTH

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Faculty of Electronics, Communications and Automation for public examination and debate in Auditorium S4 at Helsinki University of Technology (Espoo, Finland) on the 19th of September, 2008, at 12 noon.

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ISBN 978-951-22-9501-2
ISBN 978-951-22-9502-9 (pdf)
ISSN 1797-4178
ISSN 1797-4186 (pdf)

Multiprint Oy
Espoo 2008

ABSTRACT OF DOCTORAL DISSERTATION	HELSINKI UNIVERSITY OF TECHNOLOGY P.O. BOX 1000, FI-02015 TKK http://www.tkk.fi

Author Paulo Pinho

Name of the dissertation
Usage and control of solid-state lighting for plant growth

Manuscript submitted 25.03.2008	Manuscript revised 26.05.2008

Date of the defence 19.09.2008

☐ Monograph ☒ Article dissertation (summary + original articles)

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Field of research Illuminating Engineering
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Abstract
The work begins with an introductory part in which the basic aspects related to the photosynthetic radiation, the photobiology of plants and the technology of light-emitting diodes (LEDs) are overviewed. It is followed by a review of related research works that have been conducted during the last two decades, and by the main design issues of LED luminaires for plant growth. The following part of the work reports the experimental growth tests performed. The effects of the radiation emitted by spectrally tailored LED luminaires on plant growth have been investigated. A total of four growth tests using lettuce and radish cultivars were performed. Two basic approaches were used to investigate the effects and the future possibilities of the usage of solid-state lighting (SSL) in plant growth. The first approach evaluates the growth development of lettuce plants in real greenhouse conditions using LEDs as supplementary light sources to natural daylight. In the second approach the evaluation was carried out with a total absence of natural daylight by growing lettuce and radish plants in phytotron-chamber conditions. The effects of SSL treatments on the growth development and quality of crops were compared with reference lighting systems composed of conventional and well-established light-source technologies, such as fluorescent and high-pressure sodium lamps. During the process of the investigation, the need to coherently quantify and evaluate the spectral quality of the radiation in terms of its photosynthetic appetence arose. Different metrics are still been used indiscriminately to quantify radiation used by plants to perform photosynthesis. Therefore, the existing metrics are discussed and a new proposal for coherent systematization is presented. The proposed system is referred to phyllophotometric and it is developed using the average photosynthetic spectral quantum yield response curve of plants. The results of the growth tests showed that the usage of SSL in plant growth offers an unprecedented possibility to optimise the morphogenesis, the photosynthesis and the nutritional quality of crops. This can be done by controlling the quantity and the spectral composition of the radiation provided, areas where LED-based luminaires excel. These possibilities can contribute to respond to the increasing demand for high-quality horticultural products by the consumers and to the conservation of global natural environment and resources.

Keywords Light emitting diode, plant growth, control of light spectrum, solid-state lighting, phyllophotometry

ISBN (printed)	978-951-22-9501-2	ISSN (printed)	1797-4178
ISBN (pdf)	978-951-22-9502-9	ISSN (pdf)	1797-4186
Language	English (U.K.)	Number of pages	60 p. + app. 117 p.

Publisher Department of Electronics, Helsinki University of Technology

Print distribution Department of Electronics, Helsinki University of Technology

☒ The dissertation can be read at http://lib.tkk.fi/Diss/2008/isbn9789512295029

Preface

The work presented in this thesis was possible due to the interdisciplinary and collaborative work involving directly and indirectly various persons and institutions, which I would like hereafter to acknowledge.

Part of the work was carried out in national project "Kasvien valotus LED-valaistusjärjestelmällä" funded 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) between the year of 2005 and 2006. The last part of the work was accomplished during the ENLIGHTEN project funded by the European Commission's Asia-Link Programme (ASIE/2005/101320) between the year of 2005 and 2008. I would like to thank all participants in both referred projects.

To Professor Liisa Halonen, my supervisor in this work, I'm deeply grateful for her contagious and unlimited enthusiasm, for the energy and encouragement given especially during the most difficult periods of the work.

I am also grateful to my instructor Dr. Eino Tetri for all help and guidance during the accomplishment of the thesis work, as well as to Dr. Marjukka Eloholma for revising the final draft of the thesis and for the valuable comments and corrections.

I wish also to thank Professor Olavi Junttila and Professor Uli Lemmer for their priceless comments during the preliminary examination process of the thesis.

I thank also the personnel of the laboratory for their help.

My special thanks go to Pramod Bhusal and Martti Paakkinen for the relaxing and pleasant environment created while we shared the same office room. Thank you also for the innumerable enjoyable and useful discussions about work and life in general.

To Sini and Jorma Piippo, I'm grateful for all the help given during these eight years living in Finland.

Aos meus pais, Agostinho e Catarina Pinho quero agradecer-vos por terem dado o vosso melhor por mim. Estou-vos eternamente grato.

Finally, I'm deeply thankful to my wife Jarna Piippo and to our children Pauli, Siri, Sandra and Sofi for their love and patience.

Paulo Pinho

Helsinki, May 2008

List of publications

I P. Pinho, O. Moisio, E. Tetri and L. Halonen, "Photobiological aspects of crop plants grown under light emitting diodes," in *Proceedings of the CIE Symposium 04, LED Light Sources: Physical Measurements and Visual and Photobiological Assessment - Tokyo, Japan,* CIE x026:2004, 2004, pp. 71-74.

II O. Moisio, P. Pinho, E. Tetri and L. Halonen, "Controlling colour temperature of LED-luminaire," in *Proceedings of the 10th International Symposium on the Science and Technology of Light Sources - Toulouse, France,* 2004, pp. 375-376.

III P. Pinho, E. Tetri and L. Halonen, "Design and performance assessments of solid state light sources for plant growth," in *Proceedings of the 10th European Lighting Conference Lux Europa 2005: Lighting for Humans – Berlin, Germany,* 2005, pp. 297-301.

IV O. Moisio, M. Pajula, P. Pinho, L. Halonen and R. Sepponen, "Use of junction temperature in control of CCT in LED luminaire," in *Proceedings of the CIE Midterm Meeting and International Lighting Congress - Congreso Internacional De Iluminación - La Iluminación En El Siglo XXI – Léon, Spain,* 2005, pp. 328-334.

V P. Pinho, E. Tetri and L. Halonen, "Synergies of controller-based LED drivers and quality solid-state lighting," in *Proceedings of the 2nd Conference on Ph.D. Research in MicroElectronics and Electronics - PRIME 2006,* 2006, pp. 405-408.

VI A. Urbonavičiūtė, P. Pinho, G. Samuolienė, P. Duchovskis, P. Vitta, A. Stonkus, G. Tamulaitis, A. Žukauskas and L. Halonen, "Effect of short-wavelength light on lettuce growth and nutritional quality," *Scientific Works of the Lithuanian Institute of Horticulture and Lithuanian University of Agriculture - Sodininkystė Ir Daržininkystė,* vol. 26, pp. 157-165, 2007.

VII A. Urbonavičiūtė, P. Pinho, G. Samuolienė, P. Duchovskis, P. Vitta, A. Stonkus, G. Tamulaitis, A. Žukauskas and L. Halonen, "Influence of bicomponent complimentary illumination on development of radish," *Scientific Works of the Lithuanian Institute of Horticulture and Lithuanian University of Agriculture - Sodininkystė Ir Daržininkystė,* vol. 26, pp. 309-316, 2007.

VIII P. Pinho, R. Nyrhilä, L. Särkkä, R. Tahvonen, E. Tetri and L. Halonen, "Evaluation of Lettuce Growth under Multi-spectral-component Supplemental Solid State Lighting in Greenhouse Environment," *International Review of Electrical Engineering (I.R.E.E.),* vol. 2, pp. 854-860, 2007.

IX P. Pinho, T. Rosvall, E. Tetri, M. Eloholma and L. Halonen, "Light emitting diodes in plant growth: Comparative growth test in greenhouse and evaluation of photosynthetic radiation," Helsinki University of Technology, Department of Electronics – Lighting Unit, Espoo, Tech. Rep. 48, 2008.

The author has played an active role in all the stages of the work reported in the publications. He was responsible for publications [I], [III], [V], [VIII] and [IX] as the main author. The author has contributed to the design of the LED luminaries utilized during the experimental work presented in publications [VI], [VII], [VIII] and [IX].

List of abbreviations and symbols

Abbreviations

ABA	Abscisic acid
Btu	British Thermal Unit
CCD	Charge-coupled Device
CCT	Correlated color temperature
CIE	Commission Internationale de L'Eclairage
CW-LED	Cool-white phosphor converted LED
d	Distance
DAG	Days After Germination
DNA	Deoxyribonucleic acid
E	Exa
FR	Far-red radiation
FW	Fresh weigh
GA3	Gibberelic acid
HB-LED	High-brightness Light Emitting Diode
HPS	High-pressure sodium lamp
INC	Incandescent lamp
IND	Induction lamp
J	Joule
LED	Light Emitting Diode
m	Meter
MHz	Megahertz
mol	Mole
MTT	Maa- ja elintarviketalouden tutkimuskeskus
nm	Nanometer
P	Peta
PAR	Photosynthetically Active Radiation
Pfr	Far-red absorbing form of phytochromes
PPF	Photosynthetic photon flux
PPFD	Photosynthetic photon flux density
Pr	Red absorbing form of phytochromes
PWM	Pulse width modulation
R/FR	Red to far-red ratio
RB-LED	LED luminaire composed by red and blue LEDs
s	Second
SL	Sulphur lamp
SSL	Solid-state Lighting
UV	Ultraviolet
UV-A	Ultraviolet A
W	Watt
WW-LED	Warm-white phosphor converted LED

Symbols

AlGaAs	Aluminium gallium nitride
AlInGaN	Aluminium indium gallium nitride
AlInGaP	Aluminium indium gallium phosphide
c	Speed of light in vacuum
$C_6H_{12}O_6$	Carbohydrates
CO_2	Carbon dioxide
$E_e(a)$	Angular irradiance
h	Planck's constant
H_2O	Water
$I_e(a)$	Angular radiant intensity
I_{eo}	Perpendicular radiant intensity
N_A	Avogadro's number
O_2	Oxygen
P_D	Power dissipation
$P_y(\lambda)$	Relative quantum efficiency spectral curve
R_{thBA}	Thermal resistance between the board and ambient
R_{thJS}	Thermal resistance between PN junction and soldering point
R_{thSB}	Thermal resistance between the soldering point and board
SiC	Silicon carbide
T_a	Ambient temperature
T_b	Board temperature
T_j	Temperature at PN junction
T_s	Temperature at soldering point

Greek symbols

ϕ_e	Radiant power
$\phi_{e,\lambda}$	Spectral radiant power distribution
ϕ_p	Photon flux
$\phi_{p,\lambda}$	Spectral photon flux distribution
ϕ_{ps}	Phyllophotometric flux
λ	Wavelength
$\lambda_{\kappa\alpha\varepsilon\pi}$	Peak wavelength
μ	Micro

Contents

1 Introduction

1.1 Background

1.1.1 Photosynthetically active radiation

The sun, which is the nearest star to planet Earth, is the main source of visible (i.e. light) and invisible electromagnetic radiation and the main factor responsible for the existence of life. Almost one-third of the sun's radiant energy incident on Earth is reflected back to space. Nevertheless, the net daily average solar energy reaching the Earth is approximately 28×10^{23} J (i.e. 265 EBtu) [1]. This value is 5500 times higher than the world's annual primary energy consumption, estimated in 2007 to be 479 PBtu [2].

The spectral distribution of the sun's radiation, as it can be measured at the earth's surface, has a broad wavelength band of between around 300 nm and 1000 nm. However, only 50% of the radiation reaching the surface is photosynthetically active radiation (PAR) [3]. PAR, according to the CIE (Commission Internationale de L'Eclairage) recommendations comprises the wavelength region of between 400 nm and 700 nm of the electromagnetic spectrum [4]. The laws of photochemistry can generally express the way that plants harvest radiation. The dual character of radiation makes it behave as an electromagnetic wave when propagating in space and as particles (i.e. photon or quantum of radiant energy) when interacting with matter. The photoreceptors are the active elements existing mainly on plant's leaves responsible for the photon capture and for conversion of its energy into chemical energy. Due to the photochemical nature of photosynthesis, the photosynthetic rate, which represents the amount of O_2 evolution or the amount of CO_2 fixation per unit time, correlates well with the number of photons falling per unit area per second on a leaf surface. Therefore, the recommended quantities for PAR are based on the quantum system and are expressed using the number of moles (mol) or micromoles (μmol) of photons. The recommended term to report and quantify instantaneous measurements of PAR is the *photosynthetic photon flux density (PPFD)*. This gives the number of moles of photons falling at a surface per unit area per unit time. However, the term *photosynthetic photon flux (PPF)* is also frequently used in the literature to refer to the same quantity [4].

1.1.2 Light mediated processes in green plants

Specialized photoreceptors existing in living organisms such as humans, animals and plants use the radiant energy captured to mediate important biologic processes. This mediation or interaction can take place in a variety of ways. The gather of environmental and sensory information such as in vision processes or, in a more subtle way, in setting the metabolic and circadian cycles of living organisms are just a few examples.

Photosynthesis together with photoperiodism, phototropism and photomorphogenesis are the four representative processes related to interaction between radiation and plants. The following expression shows the simplified chemical equation of photosynthesis.

$$6H_2O + 6CO_2 \xrightarrow{\text{photons 'energy}} C_6H_{12}O_6 + 6O_2 \tag{1}$$

The carbohydrates, such as sugar glucose ($C_6H_{12}O_6$) and oxygen (O_2), are the main products of the photosynthesis process. These are synthesized from carbon dioxide (CO_2) and water (H_2O) using the photons' energy harnessed by using specialised photoreceptors such as chlorophylls and converted into chemical energy. Through photosynthesis, the radiant energy is also used as the primary source of chemical energy, which is important for the growth and development of plants. Naturally, the stoichiometry of the equation is also dependent on the quantity (i.e. number of photons) and quality (i.e. photons' energy) of the radiant energy and, consequently, also of the produced biomass of the plants. [I]

Photoperiodism refers to the ability that plants have to sense and measure the periodicity of radiation, *phototropism* to the growth movement of the plant towards and away from the radiation, and *photomorphogenesis* to the change in form in response to the quality and quantity of radiation. [I]

1.1.3 Photoreceptors and photosystems

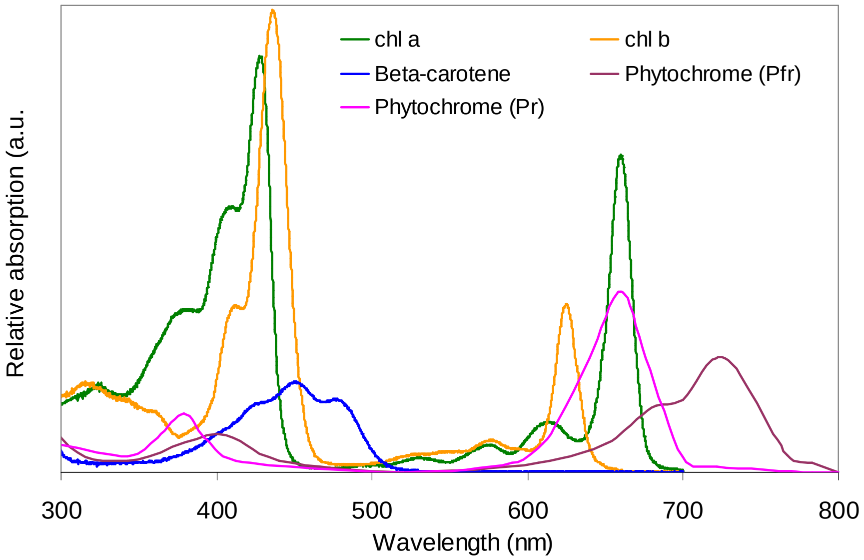


Figure 1 - Relative absorption spectra of the most common photosynthetic and photomorphogenetic photoreceptors in green plants [5, 6].

The typical absorption spectra of the most common photosynthetic and photomorphogenetic photoreceptors, such as chlorophyll *a*, chlorophyll *b* and beta-carotene, and the two interconvertable forms of phytochromes (Pfr and Pr) are shown in Figure 1. The photomorphogenetic responses, contrary to photosynthesis, can be achieved with extremely low light fluence rates. The different types of photosynthetic and photomorphogenetic photoreceptors can be grouped in at least three known photosystems: photosynthetic, phytochrome and cryptochrome or blue/UV-A (ultraviolet-A).

In the photosynthetic photosystem, the existing pigments are chlorophylls and carotenoids. Chlorophylls are located in the chloroplasts' thylakoids located in the leaf mesophyll cells of plants [7]. Here, the quantity or the energy of the radiation is the most significant aspect, since the activity of those pigments is closely related to the light harvest. The two most important absorption peaks of chlorophyll are located in the red and blue regions from 625 to 675 nm and from 425 to 475 nm, respectively. Additionally, there are also other localized peaks at near-UV (300 - 400 nm) and in the far-red region (700 - 800 nm) [1]. Carotenoids such as xanthophylls and carotenes are located in the chromoplast plastid organelles on plant cells and absorb mainly in the blue region. They are also known as auxiliary photoreceptors of chlorophyll. [I]

The phytochrome photosystem includes the two interconvertable forms of phytochromes, Pr and Pfr, which have their sensitivity peaks in the red at 660 nm and in the far-red at 730 nm, respectively. Photomorphogenetic responses mediated by phytochromes are usually related to the sensing of the light quality through the red (R) to far-red (FR) ratio (R/FR). Phytochromes are probably the most intensively investigated group of photoreceptors [8-11]. In Arabidopsis there are five identified phytochromes: phyA, phyB, phyC, phyD and phyE [12]. The importance of phytochromes can be evaluated by the different physiological responses where they are involved, such as leaf expansion, neighbour perception, shade avoidance, stem elongation, seed germination and flowering induction. Although shade-avoidance response is usually controlled by phytochromes through the sensing of R/FR ratio, the blue-light and PAR level is also involved in the related adaptive morphological responses [13]. [I]

Blue- and UV-A (ultraviolet A)-sensitive photoreceptors are found in the cryptochrome photosystem. Blue light absorbing pigments include both cryptochrome (cry1, cry2) and phototropins (phot1, phot2). They are involved in several different tasks, such as monitoring the quality, quantity, direction and periodicity of the light. The different groups of blue- and UV-A-sensitive photoreceptors mediate important morphological responses such as endogenous rhythms, organ orientation, stem elongation and stomatal opening, germination, leaf expansion, root growth and phototropism. Phototropins regulate the pigment content and the positioning of photosynthetic organs and organelles in order to optimize the light harvest and photoinhibition [14]. As with exposure to continuous far-red radiation, blue light also promotes flowering through the mediation of cryptochromes photoreceptors [15]. Moreover, blue-light-sensitive photoreceptors (e.g. flavins and carotenoids) are also sensitive to the near-ultraviolet radiation, where a localized sensitivity peak can be found at around 370 nm [1].

Cryptochromes are not only common to all plant species but are also common in humans [16, 17]. Cryptochromes mediate a variety of light responses, including the entrainment of the circadian rhythms in flowering plants such as the Arabidopsis, in mammals and in small insects such as the Drosophila [18]. Although radiation of wavelengths below 300 nm can be highly harmful to the chemical bonds of molecules and to DNA structure, plants absorb radiation in this region also. The quality of radiation within the PAR region may be important to reduce the destructive effects of UV radiation [19]. [I]

These photoreceptors are the most investigated and therefore their role in control of photosynthesis and growth is known reasonably well. However, there is evidence of the existence of other photoreceptors, the activity of which may have an important role in mediating important physiological responses in the plant. Additionally, the interaction and the nature of interdependence between certain groups of receptors are not well understood. [14, 20]

Photosynthesis is perhaps one of the oldest, most common and most important biochemical process in the world. The use of artificial light to substitute or compensate the low availability of daylight is a common practice, especially in northern countries during the winter season, for production of vegetable and ornamental crops [21-26].

1.2 Artificial radiation sources in plant growth

Since ancient periods of human existence, the sun and its radiation have exerted an almost magical attraction. Its imitation has led to the first incipient forms of artificial lighting starting with the fire. The advent of electric lighting has played an important role in the development of knowledge and consequently of technology in general. The era of artificial electric lighting started with the development by Thomas Edison in 1879 of Edison's bulb, commonly known today as the incandescent lamp. Since that period, the usage of artificial light and its technological development efforts have been mainly focused on visual performance aspects (i.e. human vision).

Due to its thermal characteristic, incandescence is characterised by a large amount of far-red emission, which can reach approximately 60% of the total PAR. In spite of the developments that have taken place over more than a century, the electrical efficiency of incandescent lamps, given by the conversion efficiency between electrical energy consumed (input) and optical energy emitted (output) within the visible spectral region, is still very poor. Typically it ranges between 9% and 12% [27]. Incandescent light sources have one of the lowest lifetime performances, typically not higher than 2000 hours. In plant-growth applications their use is limited. Growth of ornamental plants is one of the applications where incandescent lamps can still be used. Floral initiation can be achieved with long day responsive species using overnight exposure to low photon fluence rates using incandescent lamps [28, 29]. The high amount of far-red radiation emitted is used to control the photomorphogenetic responses throughout the mediation of the phytochromes.

Fluorescent lamps are more commonly utilized in plant-growth applications than incandescent lamps. The electro-optical energy conversion is more efficient in comparison to incandescent lamps. Tubular type fluorescent lamps can achieve electrical efficiency values from typically around 20% to 30%, where more than 90% of the emitted photons are inside the PAR region with typical life times of around 12000 hours [27]. However, especially designed long-lifetime fluorescent lamps can reach lifetimes of between 20000 and 36000 hours [30]. Besides their reasonable energy efficiency and lifetime, another advantage of fluorescent lamps in plant growth is the amount of blue radiation emitted. This can reach more than 10% of the total photon emission inside PAR, depending on the correlated colour temperature (CCT) of the lamp. For this reason, fluorescent lamps are frequently used for total substitution of natural daylight radiation in close growth rooms and chambers. The blue radiation emitted is indispensable to achieve a balanced morphology of most crop plants through the mediation of the cryptochrome family of photoreceptors [31].

The metal halide lamp belongs to the group of high-intensity discharge lamps. The emission of visible radiation is based on the luminescent effect. The inclusion of metal halides during manufacture allows to a certain extent the optimisation of the spectral quality of the radiation emitted. Metal halide lamps can be used in plant growth to totally replace daylight or for partially supplementing it during the period of lower availability. The high PAR output per lamp, the relatively high percentage of blue radiation around 20% [32, 33] and the electrical efficiency of approximately 25%, makes metal halide lamps an option for year-round crop cultivation. Their life expectancies are between 6000 to 20000 hours [30].

The high-pressure sodium (HPS) lamp has been the preferred light source for year-round crop production in greenhouses. The main reasons have been the high radiant emission, low price, long life time, high PAR emission and high electrical efficiency. These factors have allowed the use of high-pressure sodium lamps as supplemental lighting sources supporting vegetative growth in a cost-effective way during wintertime in northern latitudes. However, their spectral quality is not optimal for promoting photosynthesis and photomorphogenesis, resulting in excessive leaf and stem elongation [34, 35]. This is caused by the unbalanced spectral emission in relation to the absorption peaks of important photosynthetic pigments such as chlorophyll *a*, chlorophyll *b* and beta-carotene. The low R/FR ratio and low blue light emission in comparison with other sources induces excessive stem elongation to most of the crops grown under HPS lighting. Electrical efficiencies of high-pressure sodium lamps are typically within 30% and 40%, which make them the most energy-efficient light sources used nowadays in plant growth. Approximately 40% of the input energy is converted into photons inside the PAR region and almost 25% to 30% into far-red and infra red. The lifetimes of high-pressure sodium lamps are between 10000 to 24000 hours [30].

Other types of artificial light sources such as induction lamps and sulphur lamps can provide interesting solutions for plant-growth applications, mainly due to their relatively high potential energy efficiency. The operation of these electrodeless lamps is based on excitation of gases via electromagnetic emission.

Sulphur lamps emit light directly from the glowing sulphur plasma. The plasma is also an efficient radiator allowing conversion of up to 70% of input power into visible radiation [36]. Nevertheless, the typical system electrical efficiency of both technologies is close to 30%. However, in spite of the high efficiency shown and long lifetimes, the use of sulphur lighting systems has been hindered by high costs and the lifetime of magnetrons, which poses reliability problems [37]. Sulphur lamps have been evaluated for plant-growth applications [38]. They have been considered in the past the prime candidate for the development of hybrid lighting systems for bioregenerative space life support [39]. However, the high cost, noise and high emission in the blue-green region, which can reach more than 60% of the total photon emission in PAR region, may have undesirable characteristics, especially for plant-growth applications.

The low availability of daylight in northern latitudes and the demand of consumers for quality horticultural products at affordable prices year-round set demands for new lighting and biological technologies. Therefore, approaches that can reduce production costs, increase yields and quality of the crops are needed. Lighting is just one of the aspects involved that can be optimized. However, its importance cannot be underestimated. The increase in electricity prices and the need to reduce 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 in some crops approximately 30% [40]. Although existing light sources commonly used for plant growth may have electrical efficiencies close to 40%, the overall system efficiency (i.e. including losses in drivers, reflectors and optics) can be significantly lower.

The spectral quality of the radiation plays an important role in the healthy growth of the crop. The conventional light sources cannot be spectrally controlled during its utilization without the inefficient and limited utilization of additional filters. Moreover, the control of the radiation quantity is also limited, reducing the possibility of versatile lighting regimes such as pulsed operation. Therefore, and for reasons relating to the previously described aspects, the light-emitting diode (LED) and related solid-state lighting (SSL) have emerged as potentially viable and promising tools to be used in horticultural lighting.

1.3 Light-emitting diodes as photosynthetic radiation source

1.3.1 Technology

A LED is basically a junction of positively (p-type) and negatively (n-type) doped solid-state semiconductor materials. The emission of light is based on an electroluminescence effect, first reported 100 years ago by Henry Josef Round [41]. His experiments with SiC (silicon carbide), also known as carborundum, resulted in the first practical implementation of a LED. In spite of this important scientific breakthrough, the technological development of LED was relatively slow until the 1960's [42]. Red LEDs were firstly used in commercial devices such as on-off light indicators. Since then, the speed of development has gradually increased during the last two decades. Consequently, besides a light indicator, LEDs have also become a promising light source used in plant physiology research and thereafter in experimental plant-growth applications. The high potential efficiency in converting electrical power into radiant power, robustness, long life expectancy, small size and directional light emission are among the attractive characteristics of LEDs. The high potential electrical efficiency is an important aspect driving the technological development of LED technology. The use of SSL is expected to contribute to the reduction of global energy consumption by 11% by 2020 and decrease emission of CO_2 between 261 to 348 million of tons over the same period of time [43, 44].

One of the key aspects in developing LEDs is to maintain as high as possible a radiative recombination rate. This can be achieved by increasing the density concentration of carriers (electrons and holes) in the active region. Therefore, bandgap engineering, using single or multiple quantum wells and heterostructures, are commonly used in commercially available LEDs. Heterostructures are structures composed of semiconductors that have different bandgaps due to different chemical composition, while quantum wells are special cases of heterostructures. A high radiative recombination can be achieved only in semiconductors with direct bandgap energy, due to restrictions related to the momentum conservation. Binary direct bandgap alloys from groups III and V of the period table of elements have bandgaps that overlap the UV, visible and far-red spectral regions. Some of the present high-brightness LEDs (HB-LEDs) are based on ternary and quaternary alloys composed of semiconductors materials from groups III-V of the periodic table of elements. Nowadays, the three relevant systems are aluminium gallium arsenide (AlGaAs), aluminium gallium indium phosphide (AlInGaP), and aluminium indium gallium nitride (AlInGaN) [42].

Although most of the commercially available HB-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 HB-LEDs can have internal quantum efficiencies of almost 100% and 50%, respectively [45]. To achieve electrical efficiency close to these magnitudes, the external quantum efficiencies are currently being improved in order to allow more photons to escape from the LED chip without been absorbed by the surrounding structure.

1.3.2 Application in horticultural lighting

In horticultural lighting the main practical advantages of LED-based light sources in relation to conventional light sources is the directionality and full controllability of the emitted radiation. LEDs do not necessarily require reflectors, as they are naturally half-isotropic emitters. LEDs as directional emitters avoid most of the losses associated with the optics. Additionally, the narrow spectral bandwidth characteristic of coloured LEDs is another important advantage in relation to conventional broad waveband light sources.

The main advantage of using LEDs as photosynthetic radiation sources results from the possibility of selecting the peak wavelength emission that most closely matches the absorption peak of a selected photoreceptor. In fact, this possibility brings with it additional advantages. The efficiency usage of the radiant energy by the photoreceptor on the mediation of a physiological response of the plant is one of the advantages. Another advantage is the controllability of the response by fully controlling the radiation intensity. The advantages mentioned previously can be further extended to the luminaire level. One solution could be to include LEDs with different peak emissions in one luminaire and to control these in order to provide a desirable spectral emission to achieve a determined growth result or physiological response. In this way, the lighting system would allow a versatile control of lighting intensity and spectrum. Ultimately, the control of other abiotic parameters such as CO_2 concentration, temperature, daylight availability and humidity could be integrated within the same control system together with lighting, optimizing the crop productivity and the overall management of the greenhouse. [I]

The spectral emission of currently coloured AlInGaN LEDs are available from UV into to the green region of the visible spectrum. Those devices can emit in the blue and UV-A region where the absorption peaks of cryptochromes and carotenoids are located.

Chlorophyll *a* and the red isomeric form of phytochromes (Pr) have a strong absorption peak located around 660 nm. AlGaAs LEDs emit in the same region but, partially due to low market demand and outdated technology of production, they are expensive devices if compared with phosphide or even nitride-based LEDs. AlGaAs LEDs can be also used to control the far-red form of phytochromes (Pfr), which has an important absorption peak at 730 nm.

Nowadays, AlInGaP LEDs are based on a well-established material technology with the relatively high optical and electrical performance. Typically, the characteristic spectral emission region of AlInGaP red LEDs covers the region where chlorophyll *b* has its absorption peak, around 640 nm. Therefore, AlInGaP LEDs are also useful in promoting photosynthesis. [I]

1.4 Aim of the work

The overall aim of the work was to investigate the applicability of solid-state lighting technology in plant growth. This is accomplished by an extensive review of related research work conducted so far and of the results gathered from the growth tests performed.

One of the objectives was to identify the main advantages that the use of solid-state lighting could bring to horticultural lighting and to year-round crop production considering the fast development of LED technology. Therefore, two experiments were conducted in a real greenhouse environment in order to forecast the possible benefits of using solid-state lighting as supplemental lighting. A further two experiments have been conducted in a phytotron-chamber environment in order to evaluate the effects of the spectral composition of solid-state lighting on the growth and quality of lettuce and radish plants without daylight.

During the investigation process, a need arose to coherently quantify and evaluate the spectral composition of the radiation in terms of its photosynthetic appetence. As a result, a new metric system, referred to as *phyllophotometric*, was developed for the coherent measurement of photosynthetic radiation.

2 State-of-the-art

Attempts to purify air and grow food for space exploration in a sealed environment had already begun in 1965 with Bios experiments in bioregenerative life support [46]. However, only since the 1990's have several studies been systematically performed to investigate the use of LEDs as a spectrally controllable light source for plant growth applications and in bioregenerative life support systems for long interplanetary trips and colonization of other planets such as Mars. The outcome of theses studies have also unveiled and clarified certain aspects of plants' physiological and morphological responses related directly to the radiation spectral composition (i.e. radiation quality). Some of these studies are overviewed hereafter.

The potentialities of LEDs as a photosynthetic radiation source for plant growth were evaluated and confirmed in the early 1990's [47, 48]. In the initial experiments, lettuce (*Lactuca sativa* L. 'Grand Rapids') plants grown under LEDs were compared with the control plants grown under fluorescent lamps. At the beginning of the 1990's, viable blue LEDs were not available. Therefore, blue fluorescent lamps were commonly used to complement AlGaAs LEDs with peak wavelength at 660 nm. The studies have revealed that blue light was indispensable to achieve a balanced morphology of lettuce plants. The percentage of blue radiation used was around 9% of the total photosynthetic photon flux (PPF). Red LED supplemented by a blue fluorescent lamp was effective as a radiation source for growing plants. Nevertheless, the results could not be used to clearly conclude that plant growth under the LED array complemented with a blue fluorescent lamp system was greater than plants grown only under cool-white fluorescent lamps or incandescent lamps for the same period of time with equivalent PPF. Estimations of the electrical energy conversion efficiency of the red LED system were found to be twice as much as published for fluorescent lamps. These two studies agreed about the viability of using LEDs as a radiation source for plant growth, although red LEDs alone only were not sufficient to promote an ideal growth.

A comparison between spectral regimes using cool-white fluorescent lamps and red LEDs complemented with blue fluorescent lamps revealed that the cool-white fluorescent lamps alone were more effective in the inhibition of the hypocotyls and cotyledons growth of lettuce seedlings [49]. This was explained partially by the fact that the blue spectral region of cool-white fluorescent lamps appeared to have some differences in relation to the spectrum of blue fluorescent lamps used together with the LEDs. Additionally, the greater amount of UV radiation emitted by cool-white fluorescent lamps was believed to benefit the activity of flavoproteins in the inhibitory action of the hypocotyls. Cool-white fluorescent lamps also emit in red and infrared regions and therefore phytochrome might have been activated in a way that could justify an interacting effect on elongation. It was also concluded that a certain amount of elongation is necessary. Therefore, 15 to 30 μmol m^{-2} s^{-1} of a photosynthetic photon flux density with a 12-h photoperiod due to blue radiation would be acceptable for lettuce growth. The findings of earlier studies were also confirmed in the sense that lettuce seedlings respond to a specific number of blue photons rather than to a ratio between the blue photosynthetic photon flux and the total photosynthetic photon flux.

Another study conducted during the early 1990's has also concluded that LEDs were good candidates to be used as light sources for plant growth in space [50]. The main reasons pointed out were the energy efficiency potential, small size, safety, reliability, optimal spectral output for photosynthesis and photomorphogenesis. Among the advantages verified was the fact that the percentage of non-photosynthetic emission of LEDs was very low, unlike high-pressure sodium, metal halide and cool-white fluorescent lamps, with 41%, 32,5%, and 8,6%, respectively. However, it was concluded that the main advantage of LEDs systems was that their peak spectral emission could be selected to closely coincide with the wavelength of the maximum photosynthetic quantum action of plants. Thus, the photosynthetic utilization efficiency and net assimilation rates of plants would be expected to be greater than with other radiation sources at equal photosynthetic photon fluxes. In terms of utilization, it was shown that the effectiveness of LEDs may be increased if pulsed radiation in the megahertz frequency range (e.g. 2 MHz) is used. At short duty cycles smaller than 10%, the instantaneous photosynthetic photon flux during pulses can be up to six times greater than the level maintained during continuous operation. This would allow the devices to be powered at instantaneous forward currents significantly greater than with continuous operation due to the cooling period allowed between pulses.

The development of a complete solid-state light source solution for plant applications was hindered by the lack of a viable blue LED. In 1993, after long years of difficulties, Shuji Nakamura developed the first viable high-brightness blue LED based on InGaN material alloy [51]. This breakthrough allowed that a complete solid-state light source for plants growth was developed [52]. The peak emission wavelength of the newly developed LED was at 450 nm. This wavelength was close enough to the maximum absorption peak of carotenoids photoreceptors in plants. In the same year, successful growth of lettuce seedlings using only red and blue LEDs was achieved. The spectral regime was composed of a mixture of 33% blue and 67% red radiation [53]. Following this, several growth chamber apparatuses were developed using low-power red, blue and far-red LEDs with peak wavelengths of 660 nm, 450 nm and 730 nm, respectively.

Acceptable growth of spinach plants (*Spinacia oleracea* L. cv. Minsterland) with red LEDs was verified when compared with plants grown under special fluorescent lamps spectrally designed for plant growth [54]. Plants grown under red LEDs were two times higher and had leaf area two times smaller than plants grown under fluorescent lamps. Based on this, an association between the enlargement of the spinach leaf and blue light was also established.

The importance of blue light was further studied for pepper plants (*Capsicum annuum* L. cv., Hungarian Wax) [33]. The primary objective was to compare the anatomical features of leaves and stems of pepper plants grown under different spectral regimes provided by LEDs. It was found that the absence of blue photons or an increase in the R/FR ratio can reduce the thickness of mesophyll tissues in pepper. They found that 4 µmol m^{-2} s^{-1} (around 1% of the total PPF) was the minimum amount of blue radiation required to complement the emission of red LEDs in order to mitigate most of the plant-growth differences. Finally, it was concluded that the effects of blue light should be isolated from the total PPF and R/FR when studying the effects of spectral composition of the radiation on the plants' anatomy. Moreover, low levels of blue light can induce dramatic changes in the anatomy of pepper plants.

The importance of the spectral composition of the light in controlling the development of diseases has been evaluated using LEDs [55]. It was observed that the disease caused by the tomato mosaic virus in pepper plants developed slower, and was less severe, under lighting systems that emitted in the blue and UV-A regions. Conversely, the number of colonies per leaf of powdery mildew on the cucumber plants was larger on leaves grown under light sources with higher emission in blue and UV-A regions. The use of far-red together with red LEDs with peak wavelengths at 735 nm and 660 nm, respectively, has increased the colony counts per leaf of powdery mildew in cucumber. Finally, it was concluded that LEDs with peak wavelengths in blue, UV-A, and possibly FR regions, can modify disease development of plants. However, the mechanisms interfering with the development of those diseases were not completely unveiled.

No influence on the total leaf area and total dry weight of white clover was verified due to blue light exposure, although changes in the dry weight distribution have been measured [56]. This has demonstrated that blue light photoreceptors are not only involved in the perception of shade conditions but also in the subsequent biomass partitioning in white clover.

The results of growth experiments made with lettuce plants revealed that the addition of 10% blue light provided by blue fluorescent lamps to the emission of an LED array composed of red LEDs with peak emission at 660 nm was not sufficient to achieve the same growth of plants grown under cool-white fluorescent lamps [57]. In the experiments, radish, lettuce and spinach plants were grown for 21 days with equal PPF of 300 µmol m^{-2} s^{-1}. A photoperiod of 18 hours light and 6 hours dark was used for radish and lettuce and 12 hours light, 12 hours dark, for spinach. Results indicated that red LEDs alone were unacceptable for good growth of lettuce, radish and spinach. The addition of blue light greatly improved the growth but this was still not as good as cool-white fluorescent lamps for radish and spinach. However, good growth of lettuce can be achieved only with red and blue LEDs. For radish and spinach, the same light treatment might have been lacking some other wavelength component for optimal growth.

Additionally, blue light was found not to be the only reason for the growth differences found in plants grown hydroponically at six levels of blue PPF using high-pressure sodium and metal halide lamps [58]. Temperature was maintained at 26°C during the day and at 22°C at night with relative air humidity of 70% and elevated CO_2 concentration of 1000 µmol mol^{-1} with a photoperiod of 16 hours light and 8 hours dark. The light treatments conducted with the same amount of blue photons (6%) produced significantly different chlorophyll concentrations, dry masses, leaf areas and specific leaf area in lettuce. The same results were obtained and confirmed at two PPF levels of 200 and 500 µmol m^{-2} s^{-1}. It seems that, in lettuce, certain wavelengths act in conjunction with blue light to affect plant growth. It was also concluded that 'yellow' light (580 - 600 nm) appears to inhibit lettuce growth by suppressing chlorophyll or chloroplast formation. This characteristic may be unique for some species including lettuce. Nevertheless, the findings of the effects of yellow and green light in plant growth were still controversial.

The effects and the interaction of different spectral regions on the stomatal conductance behaviour of lettuce plants was evaluated under four different light treatments using red and blue LEDs, red and blue LEDs supplemented with green fluorescent lamps, green fluorescent lamps and cool-white fluorescent lamps [59]. All light treatments had the same photoperiod of 18 hours light and 6 hours dark. Similar and constant PPF of around 150 µmol m^{-2} s^{-1} (9,7 mol m^{-2} d^{-1}) was used. The results showed that the specific leaf area (i.e. leaf area per unit of dry mass) was greater under green fluorescent lamps followed by the red and blue LED, red and blue LEDs supplemented with green fluorescent lamps and cool-white fluorescent lamp treatments. The leaf area and the shoot fresh mass were largest in plants grown under red and blue LEDs supplemented with treatment with green fluorescent lamps, followed by cool-white fluorescent lamps, red and blue LEDs and green fluorescent lamps. The shoot dry mass had similar evolution; this was highest under red and blue LEDs supplemented with treatment with green fluorescent lamps, followed by red and blue LEDs, cool-white fluorescent lamps, and green fluorescent lamps. The differences in growth appeared to be originated from differences in the amount of green light rather than changes in the red light, considering that the amount of far-red radiation was very low and the blue light level influence was negligible. The same experiment also verified that green light can revert the blue-light-stimulated stomatal opening in lettuce plants.

A four-spectral component solid-state lighting facility composed of high-brightness LEDs with peak emission at 640, 660, 455 and 735 nm, respectively, were successfully used to study certain physiological aspects of lettuce radish and onions plants, namely the concentration of photosynthetic pigments under the influence of different light spectra and circadian cycle [60]. It was found that the most effective light treatment for green mass accumulation and a more balanced morphogenesis was composed of 6,4% of blue, 85% orange, 6,6% red and 2% of far-red components. The photoperiod used was 16 hours light and 8 hours dark with a thermal regime of 21/17°C.

Blue light provided by high-brightness LEDs (455 nm), have also been tested for supplementary high-pressure sodium lamps to grow tomato (*Lycopersicon esculentum* 'Trust') and cucumber (*Cucumis sativus* 'Bodega') plants [61]. The combination of conventional illumination with high-pressure sodium lamps and inner canopy blue light illumination with LEDs resulted in increased plant biomass and fruit yield, but did not offset the negative effect of extended photoperiods. The inner canopy blue light was useful for cucumber but not for tomato.

The previous studies have shown that the photosynthesis, photomorphogenesis, germination, flowering, accumulation of biomass and the phytochemical composition of crops can be controlled and optimised throughout the light provided by LEDs. Therefore it is expectable that the food production industry and consumers may benefit with the use of LEDs for plant growth in the future. Nevertheless more research work still has to be carried out in order to unveil and better understand the effects caused by the green-yellow spectral regions on the development of the crops. Moreover, the interaction and overlapping on the mediation of physiologic responses between known and unknown group of photoreceptors remains to be further elucidated.

Although acceptable growth of vegetable crops such as lettuce has been achieved using red and blue LEDs, others crops such as radish and spinach might require light with improved spectral composition. Moreover, the majority of the studies above referred have focused on the vegetative and reproductive growth aspects of crops grown under LEDs in phytotron or in growth rooms and chambers conditions. However, for year-round crop production, artificial light is commonly used to supplement the natural daylight during the seasons of lower availability. Very few study reports related with the usage and control of LEDs as supplemental light source to daylight in real greenhouse conditions were carried out.

3 Aspects of luminaire design

3.1 Optical

Due to the relatively low radiant output of LEDs in comparison to conventional light sources, LED luminaires often are composed of a discrete number of LEDs connected together to form an array. For near-field applications, where the vertical distance from the luminaire to the plant canopy is less than five times the size of the LED array, the PPF level in the plant canopy is determined by considering the individual contribution of each LED composing the array. This is determined using the inverse square law by considering the LED as a point source.

For LEDs with perfect Lambertian emission, the spatial distribution of the radiant intensity is given by

$$I_e(\alpha) = I_{eo} \times \cos\alpha \qquad (2)$$

where $I_e(\alpha)$ is the angular radiant intensity of the LED at an angle α from the vertical plane and I_{eo} is the radiant intensity in a direction perpendicular to the horizontal plane. The angular irradiance $E_e(\alpha)$ at the calculation point located on a horizontal plane at a distance d from an LED is given by

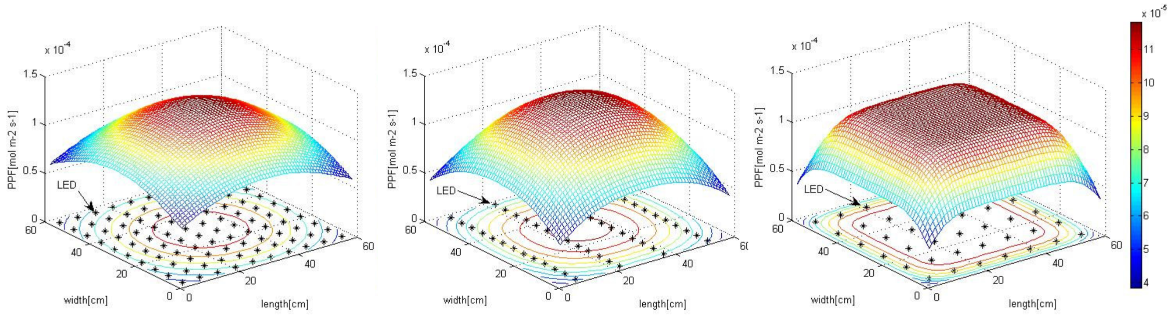
$$E_e(\alpha) = \frac{I_{eo}}{d^2}\cos\alpha \qquad (3)$$

The irradiance can be converted into photon flux by

$$E_p(\alpha) = \frac{\lambda_{peak} \times I_{eo}}{N_A \times h \times c \times d^2} \times \cos\alpha \qquad (4)$$

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. [III]

LEDs have half-isotropic spatial emission, which makes them directional emitters. Nevertheless, some of the emitted photons propagate in directions defined by large viewing angles. Thus, depending on the mounting height, a significant portion of the light emitted can be misused. The use of collimator lenses as secondary optics or LEDs with a small viewing angle can improve the lighting efficiency by directing the light towards the area to be illuminated. Collimator lenses have a high optical coupling efficiency of around 80% and 90%. Collimators are encapsulating lenses that can reduce the number of LEDs required to achieve the desired PPF. Figure 2 shows the influence of collimating lenses on the PPF spatial distribution of a 60 by 60 cm LED array at 30 cm distance from the horizontal plane. [III]



a) b) c)

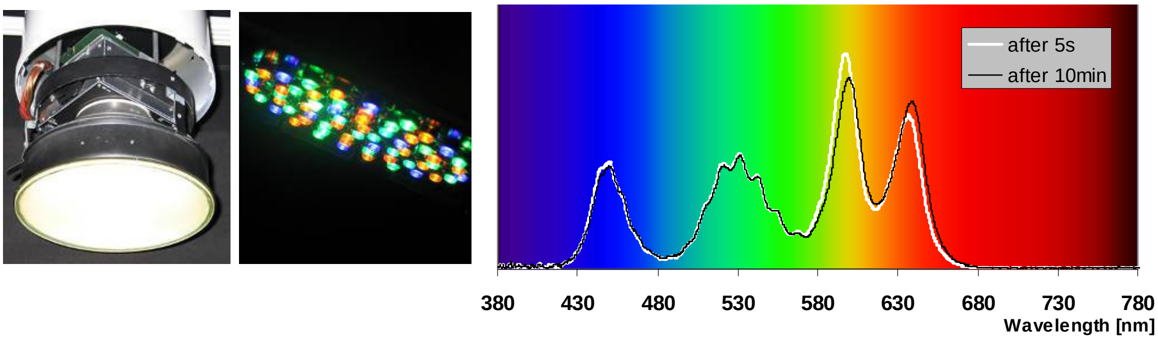
Figure 2 - PPF spatial distribution of a 60 by 60 cm LED array composed of Lambertian emitters at 30 cm distance from the horizontal plane a) *without collimating lenses*, b) *with 60°- collimating lenses and* c) *with 30°- collimating lenses.* [III]

Figure 2 indicates that the number of LEDs can be reduced by collimating the light emitted at the expense of some uniformity. While 90 LEDs without secondary optics are required to achieve a PPF of 100 µmol m^{-2} s^{-1}, only 42 LEDs are needed with 30°-collimating lenses. In this case the PPF uniformity, defined by the minimum-to-average ratio, would decrease from 60% to approximately 38%. However, the uniformity criteria may not be qualified if energy efficiency of lighting is emphasized. If in Figure 2a and Figure 2b the areas with PPFs higher than the average value of 100 µmol m^{-2} s^{-1} (yellow lines) are compared, it can be seen that the collimating lens option results in the higher area. These results have shown that the utilization of collimating lenses can improve the light utilization efficiency by reducing the light waste. [III]

The use of artificial light for supplementing daylight during the winter season in northern latitudes requires luminaries with a small form factor in order to reduce shadowing. Additionally, the luminaries should have as high a photon flux as possible to reduce the number of luminaries required with acceptable uniformity. With the use of collimating lenses, the luminaire mounting heights can be increased while maintaining the number of LEDs acceptable without reducing the average PPFs.

An important advantage of LED-based lighting over conventional light fixtures is the possibility of control of the flux emission and the spectrum of the light. By selecting the most appropriated light spectrum the plant growth in terms of photosynthesis and morphogenesis of the crops can be optimized. The control of the light spectrum allows the optimization of the photosynthesis and provides additional growth control of the crops. The control of correlated colour temperature of white light produced by multi-spectral component LED luminaires has brought new possibilities to lighting design. [II]

Most of the techniques used to control the CCT of such luminaires can also be applied to plant growth to control and maintain the light spectrum appropriate for the photosynthesis. One of these techniques uses the indirect measurement of the junction temperature of the LEDs composing the array. [IV] The light output and the characteristic spectral distribution of LEDs are dependent on its junction temperature. Therefore, it is required to determine and maintain as constant as possible junction temperatures in order to reduce the light spectrum variations when operating in a thermal dynamic environment. [V]



a) b)

Figure 3 - a) *Prototype of a multi-spectral-component LED luminaire, with adjustable CCT control;* b) *Relative spectral power distribution at 5 seconds and 10 minutes after switch on.* [V]

The possibility of controlling the light spectrum of LED luminaires in plant-growth applications brings large possibilities of optimizing the growth of crops under artificial lighting further. Intelligent solid-state light sources integrating programmable microcontrollers, power conditioning and LED arrays will allow compact and practical fixtures for better market acceptance. Digitally controllable multi-spectral component LED luminaires such as the one shown in Figure 3 may become a reality in horticultural lighting also. However, additional scientific knowledge on photobiology and physiology of plants is still needed in order to make full use of this possibility offered by LEDs. [V]

3.2 Thermal

Photons generated in the active region are partially absorbed inside the device due to the internal structure configuration resulting in heat losses. Additional heat losses are generated due to technological and material hurdles involving the growth of epilayers composing the semiconductor chip. These heat losses have to be conducted to the exterior of the LED package in order to avoid the premature failure of the LEDs. Thus, passive or active cooling solutions have to be employed in order to minimize the negative effects of temperature increase on the optical and electrical performance of LEDs.

Although the light output has been constantly and rapidly improved following the Haitz's law [62], the energy efficiency has been marked by a slower pace. Nevertheless, commercially available high-power phosphor-converted white LEDs are nowadays more efficient than incandescent lamps by a factor of four and are rapidly catching up with the energy performances of linear fluorescent lamps. Although the internal quantum efficiency of most of the commercially available LEDs can approach almost 100% [45], the extraction techniques of the generated photons to the exterior of the device are not yet optimal.

The thermal performance of high-power LEDs should be taken into account in the early stages of luminaire design. The thermal management of high-power LEDs relies primarily on conduction and secondly on natural convection of the heat generated during the operation. Therefore, the thermal resistance of the heat path from the junction to the exterior of the device has to be reduced as much as possible for the sake of reliability and performance. Commonly, external cooling systems are used to avoid the junction temperature in order to overcome the maximum allowable temperature defined by the manufacturer.

In general, the LED technical data provided by the manufacturer's datasheet are based on operation at junction temperatures of 25°C. In most of the applications, operation at this junction temperature is not possible and the temperatures are higher. This results in a decrease in light output, making the thermal management an important design aspect. Therefore, the maximum ambient temperature expected during the operation of the LED or the LED system should be used to determine the appropriated value of the thermal resistance of the external cooling system. Figure 4 shows a simplified equivalent thermal circuit of an LED placed on a thermally conductive substrate with the required cooling system. [III]

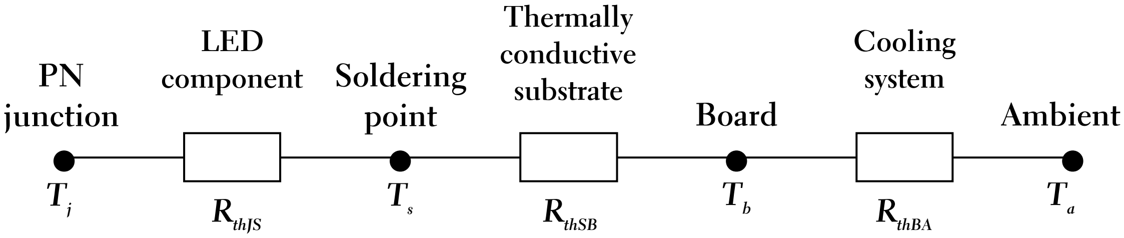


Figure 4 - Simplified thermal circuit of an LED placed on an external heat sink (cooling system) throughout a thermally conductive substrate. [III]

The thermal resistance between the PN junction and the ambient (R_{thJA}) is given by

$$R_{thJA} = \frac{T_j - T_a}{P_D} \qquad (5)$$

where T_j and T_a are the temperature of the PN junction and the ambient temperature, respectively.

The maximum thermal resistance value required for the cooling system to maintain the junction temperature below the maximum value specified by the manufacturer is given by R_{thBA},

$$R_{thBA} = R_{thJA} - (R_{thJS} + R_{thSB}) \qquad (6)$$

where P_D is the total power dissipation of the LED, R_{thJS} the thermal resistance from junction to soldering point and R_{thSB} the thermal resistance of the substrate.

3.3 Electrical

The electrical efficiency is an equally important design aspect. The overall electrical efficiency is commonly given by the ratio of the input power to the radiant output power inside the PAR region. The efficiency of the electronic drivers and LEDs should be as high as possible to maintain optimally the overall efficiency of the LED luminaire. Nowadays, constant current LED drivers have electrical efficiencies ranging between 70 to 95%, depending on their output power ratings and circuit topologies. Commercially available red and blue power LEDs commonly used to compose the basic spectrum for plant growth have electrical efficiencies of around 30% at 25°C junction temperature. Switched-mode constant current drivers are the most common, efficient and reliable solution to drive LEDs. Moreover, they easily allow dimming control features based on pulse width modulation (PWM). Figure 5 shows a typical efficiency curve common to most of the commercially available switched-mode LED drivers. The curve shows that it is recommended to maintain the operation point close to the nominal power of the driver in order to maintain the good electrical performance of the driver. [III]

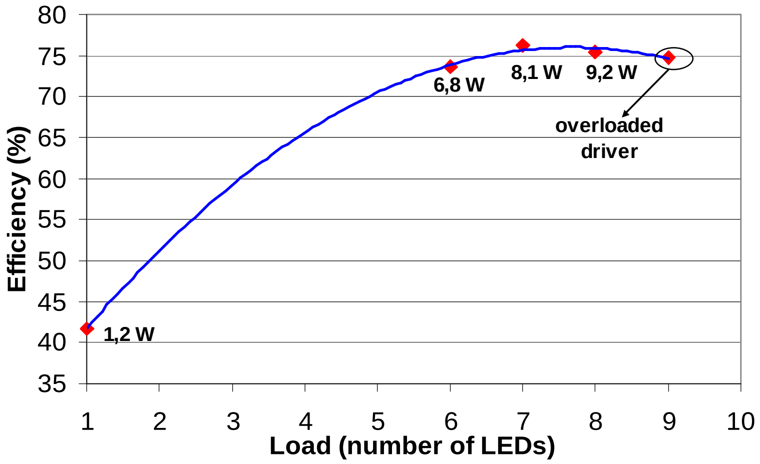


Figure 5 - Typical tendency curve of the electrical efficiency with load of a commercially available 10-W LED driver. [III]

The design and fabrication of spectrally adjustable LED luminaires to support research in plant growth can also be simply executed using linear current-controlled power supplies [63]. However, these types of driver solutions are less energy-efficient than switched-mode power supplies. Therefore, they are not indicated to be used in large solid-state lighting installations for commercial crop growth.

4 Experiments

Four growth tests were performed to investigate the effects of light spectrum on plant growth and quality by using specially designed multi-spectral component LED luminaries. Two growth tests (T1, T2) were accomplished in greenhouse conditions and two tests (T3, T4) in phytotron chamber conditions. The greenhouse approach emphasises the use of LEDs as light supplemental to daylight. The phytotron approach was used to investigate the utilization of the spectrally tailored light provided by LEDs in the development of crops.

4.1 Greenhouse growth tests

Two growth tests, T1 and T2, were conducted at MTT's (Maa- ja elintarviketalouden tutkimuskeskus / Agrifood Research Finland) greenhouse facilities in southern Finland.

4.1.1 Test conditions

The experiment site, shown in Figure 6, is located at (60°23'N/22°33E) in the Piikkiö region.

Figure 6 - Experiment site at MTT's Plant Research Group greenhouse facilities in Piikkiö, southern Finland.

The growth tests were carried out during winter when the daylight availability is the lowest and when the utilization of supplemental lighting is economically viable in northern latitudes [23, 26]. 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.

The first greenhouse growth test (T1) was conducted between January 17th and March 1st 2005. During the growth test, lettuce (*Lactuca sativa* var. crispa L., 'Frillice') plants were grown in peat substrate with a 20 hours light and 4 hours dark photoperiod 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. [VIII]

Three supplemental lighting treatments were used in this first growth test. One of the treatments was used to grow control plants utilizing conventional high-pressure sodium lamps. In the other two lighting treatments, (LED1 and LED2), LED-based luminaires were used. The lighting for the LED1 treatment was provided by a combination of AlInGaP red-orange and InGaN blue LEDs in the same luminaire. In LED2 together with red-orange and blue LEDs, AlInGaP yellow LEDs were also included. The peak wavelength emission of the blue, yellow and red-orange LEDs in real operation conditions were 460 nm, 594 nm and 630 nm, respectively. The resultant spectral distributions of the lighting treatments are shown in Figure 7. In LED1 treatment, the red-orange component was 80% of the total supplemental PPF. For LED2 treatment, the amount of the red-orange component was reduced to 59%, while a third component in yellow, representing 17% of the total PPF, was added. The short-wavelength component in the blue region was similar for both LED treatments. The relative amount of blue photon flux was 20% and 24%, respectively, for LED1 and LED2. The total average photosynthetic photon flux contributions of the supplemental lighting systems were between 75 and 90 μmol m^{-2} s^{-1}. [VIII]

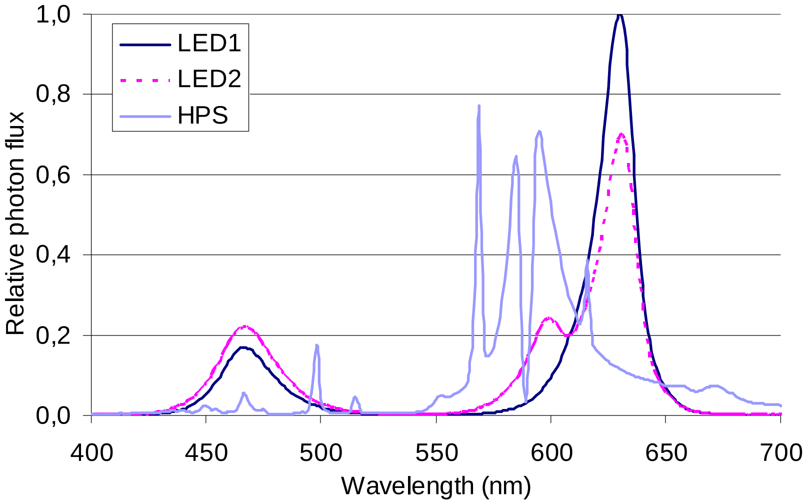


Figure 7 - Relative spectral photon flux distribution of LED lighting treatment (LED1, LED2) and high-pressure sodium (HPS) lighting treatments used to grow the control plants. [VIII]

The second growth test (T2), was conducted between February 9th and March 22nd in 2006. This was the continuation of the work started with T1. Therefore, the same plant material, growth methods and environmental parameters were used during the second greenhouse test. During this test, only one LED system composed of orange-red and blue LEDs was used. In T2, yellow LEDs were not included due to their relatively low overall electro-optical performance in comparison to orange-red and blue LEDs.

The goal of the growth test T2 was to have a larger scale experiment involving a large number of plants in order to have more appropriated statistic results. Additionally, the plant growth under the bi-spectral component LED luminaire composed of red-orange AlInGaP and blue InGaN LEDs was further investigated and compared with control plants grown under high-pressure sodium lamps.

The comparison of the fresh weight, dry weight, leaf length, leaf area and leaf number of lettuce plants grown under LED and HPS light treatments was performed through ANOVA and t-test. The statistical analysis was performed using the SPSS software program, version 14.0 (SPSS, Inc.).

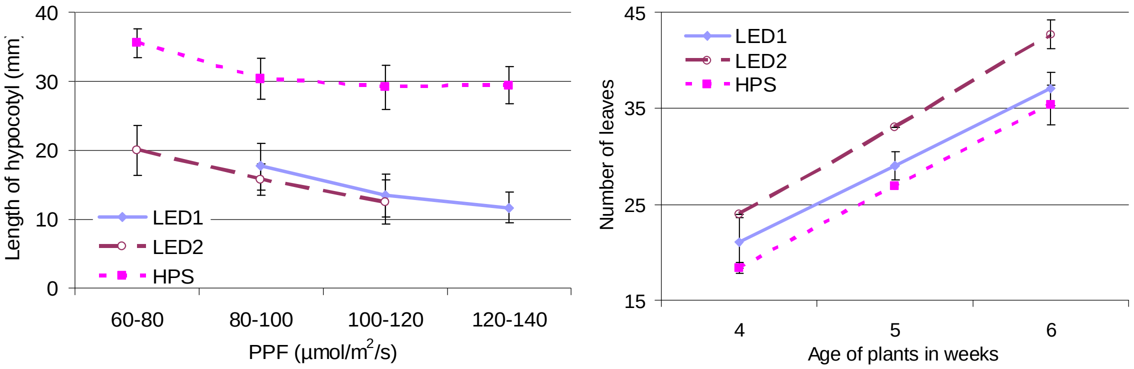
The experimental set-up of T2 was composed of two lighting treatments and respective replications. Therefore, two growth blocks were used to grow control plants using conventional high-pressure sodium lamps, while in the rest of the blocks LEDs were used. Figure 8 shows the arrangement of two of the growth blocks. In the LED blocks, the red-orange spectral component accounted for 85% of the total average PPF, while the blue component accounted for 15%. The peak wavelengths and the LED types used were the same as in T1. The total average PPF used was 180 μmol m^{-2} s^{-1}. [IX]

Figure 8 - Panoramic view of two of the growth blocks composed of LED luminaires (left) and high-pressure sodium luminaires (right) used in T2 test during week 2 on March 1st 2006 at 7:29 AM. [IX]

In this growth test the fresh weight and the dry weight of 12 plants in each growth block was measured weekly from week 2 to week 6. This represents a sample population per week of 24 plants per each light treatment taken into account the replication blocks. In each week a total of 48 lettuce plants have been measured representing 240 plants during the whole duration of the growth test. Guard plants were placed on the boarders around the plants used in the measurements.

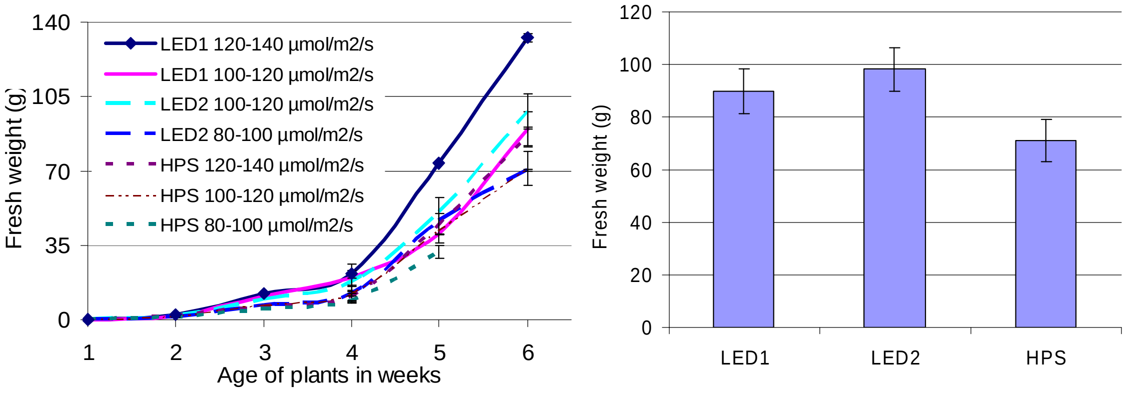
4.1.2 Results

The 20% of blue light used in the LED1 and LED2 in the first growth test T1 was sufficient to reduce hypocotyls elongation by a factor of two in relation to control plants, as shown in Figure 9a. Further on the increase of light intensity was found to contribute to the reduction of the hypocotyls elongation. The smaller hypocotyl sizes higher number of leaves and larger leaf areas of plants grown under LED1 and LED2 treatments in comparison to control plants resulted in more compact foliages and improved morphology. [VIII]



a) b)

Figure 9 - a) *Hypocotyl length at different supplemental PPF levels at end of week 1;* b) *Evolution of leaf number between week 4 and week 6 for plants grown under 100-120µmol m*$^{-2}$ *s*$^{-1}$ *supplemental PPF.* [VIII]



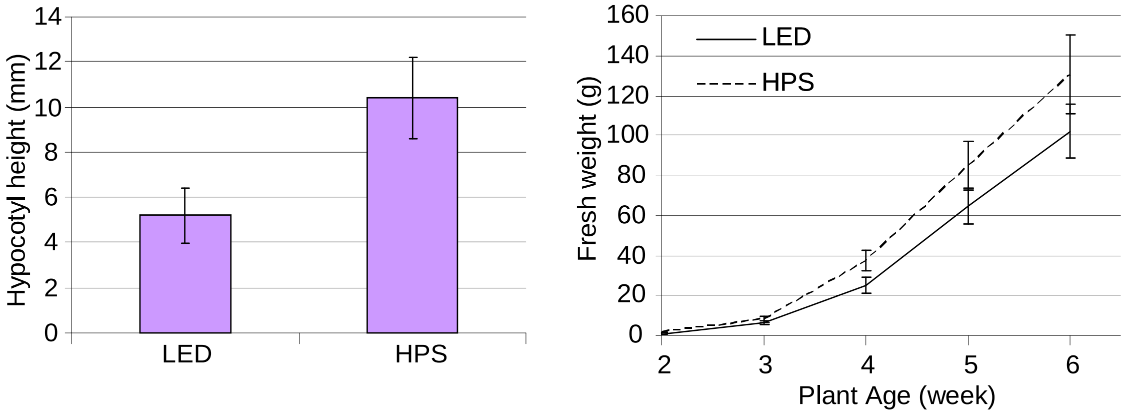
a) b)

Figure 10 - a) *Evolution of fresh weight between week 1 and week 6 at different supplemental PPF levels;* b) *Averaged fresh weight at the end of the grow test for plants grown under 100-120 µmol m*$^{-2}$ *s*$^{-1}$ *supplemental PPF.* [VIII]

For lettuce, the number of leaves per plant is relevant in terms of morphology. Figure 9b shows that the highest number of leaves was obtained with LED2 lighting treatment, which included 17% yellow light provided by LEDs peaking at 594 nm for a total supplemental PPF between 100 and 120 µmol m^{-2} s^{-1}.

At the end of the growth test, the fresh weight (FW) was approximately 53% higher for LED1 plants than for the control plants grown under a PPF between 120 and 140 μmol $m^{-2} s^{-1}$, as shown in Figure 10a. [VIII]

The lighting treatment LED2 containing the yellow component was the most effective in the accumulation of fresh weight at the end of week 6 for plants grown under 100 to 120 μmol $m^{-2} s^{-1}$ of supplemental PPF, as shown in Figure 10b. It was also verified that the increase of PPF level resulted in higher fresh weight accumulation in LED-grown plants in comparison to control plants. Similarly, for the same time period and PPF increase, the increment of the leaf-area expansion rate was almost 30% higher for plants grown under the combination of red-orange and blue lighting components (LED1) than under the high-pressure sodium light treatment. [VIII]



a) b)

Figure 11 - a) *Average hypocotyl height and standard deviation of LED- and HPS grown plants on February 22nd 2006 (week 2);* b) *Evolution of lettuce average fresh weight and respective standard deviation between week 2 and week 6.* [IX]

In the second greenhouse growth test T2 the hypocotyl height of LED grown plants was reduced by a factor of two in relation to plants grown under HPS as shown in Figure 11a. The average hypocotyl height of plants grown under LED and HPS light treatment at week 2 was 10,44 ± 1,83 mm and 5,21 ± 1,24 mm, respectively.

During the whole test, the fresh weight was highest for the HPS-grown plants, as shown in Figure 11b. At the end of the growth test in week 6, the average fresh weight of HPS and LED grown plants was 130,45 ± 19,99 g and 102,09 ± 13,15 g, respectively. A similar tendency was observed for the dry weight. However, the dry matter content for the LED-grown lettuces was at the beginning of the experiment 11% higher than for the control plants. Between week 2 and week 6, the averaged difference was approximately 7.6%.

HPS-grown plants had at week 6 more leaves than LED-grown plants. HPS-grown plants had in average 12,53 ± 0,74 leaves while LED grown plants had 11,47 ± 0,44 leaves. Although the difference in the mean number of leaves between HPS and LED grown plants was approximately one leaf, the difference is statistically significant ($p < 0,05$).

Also the average leaf area and leaf length measured at week 2 and week 3 respectively, were higher for lettuce plants grown under HPS lamps. The average leaf area of plants grown under HPS lamps and under LEDs at week 2 was 39,05 ± 7,86 cm^2 and 27,33 ± 6,13 cm^2, respectively. The average leaf length at week 3 was 10,18 ± 0,40 cm and 8,14 ± 0,35 cm for HPS and LED grown plants, respectively.

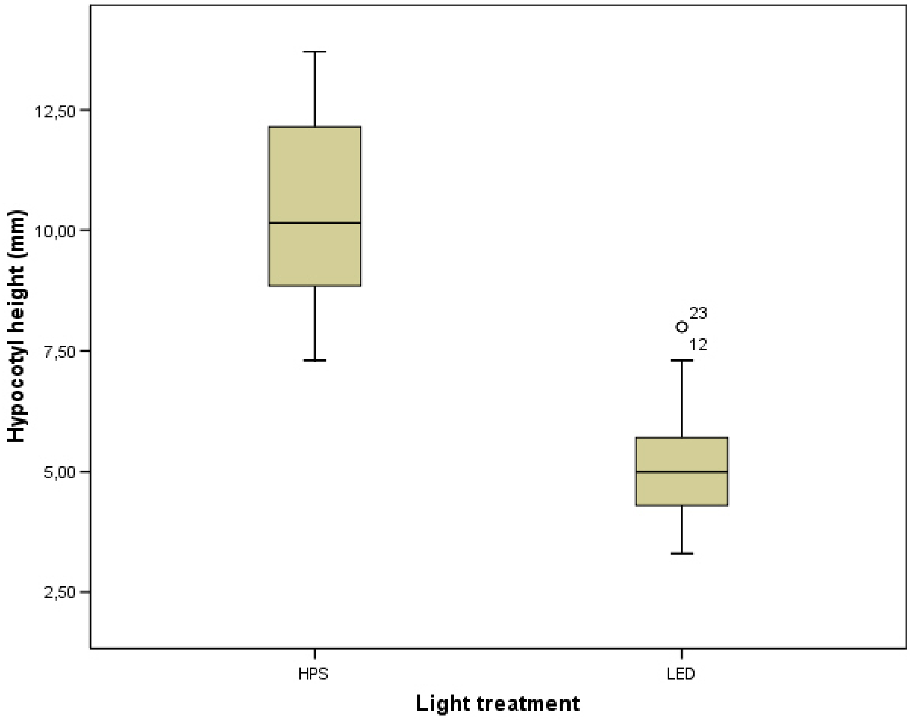


Figure 12 – Comparison of the boxplot of the hypocotyl height measured at week 2 for LED- and HPS-grown plants.

The statistical analysis of the hypocotyl measurement results show that the dispersion range of the data is clearly wider for HPS-grown plants as shown in Figure 12. Similar tendency is observed for the interquartile range. In spite of the two upper outlier measurement values, market by the circle in Figure 12 for the LED-grown plants, the average hypocotyl value is still clearly below the average value determined for the HPS-grown plants.

The Figure 13 shows the evolution between the week 2 and week 6 of the measurement dispersion range for the fresh weight of plants grown under HPS and LED light treatment. Also here it can be seen that the sample populations of plants grown under LED light treatment were more similar than the sample populations grown under the HPS light treatment during the experiment duration.

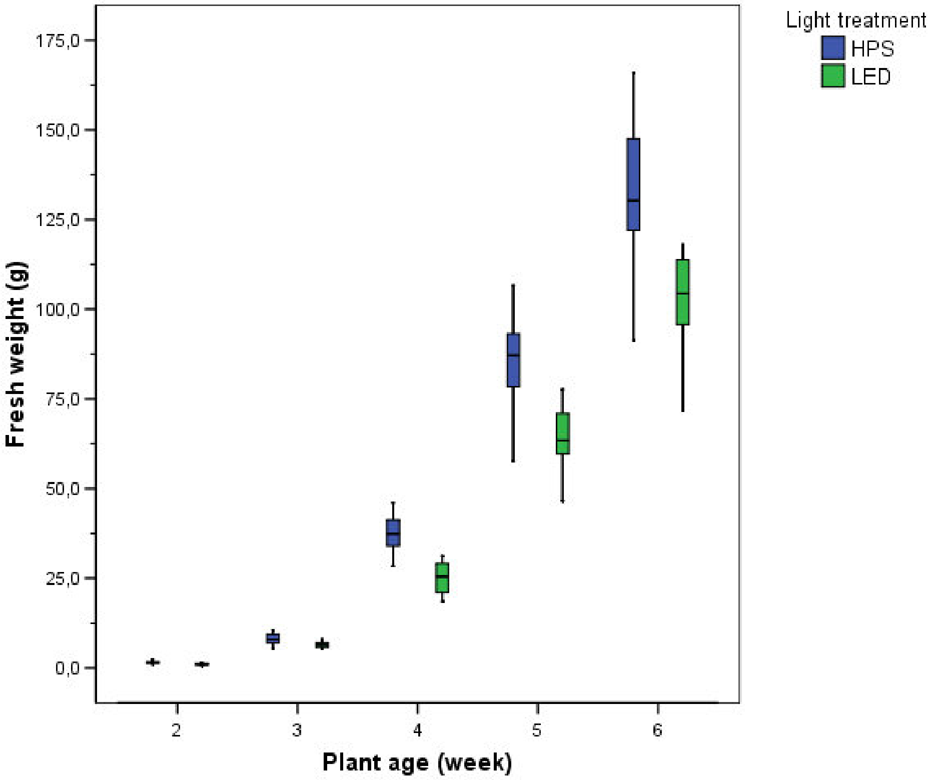


Figure 13 - Comparison of the fresh weight dispersion measurement range of LED- and HPS-grown plants between weeks 2 and 6.

Measurements performed during cloudy and sunny days did not reveal significant leaf-temperature differences between plants grown under LEDs or high-pressure sodium lamps. However, the leaf temperature of plants grown under the LED luminaires was between 0,4°C and 0,8°C lower than with plants grown under the HPS luminaires.

By visual comparison of the leaves of LED- and HPS-grown lettuce plants, it was observed that the leaves of lettuce plants grown under the LED lighting treatment were greener than the leaves of the control plants. This might be an indication of higher concentration of chlorophylls on the leaves of the LED-grown lettuces. Moreover, although no measurements were carried out, it is interesting to speculate that this observation may indicate a higher content of antioxidant vitamins characteristic of dark-green leafy vegetables.

4.1.3 Discussion

It is important to maintain the abiotic conditions similar in comparative plant-growth experiments. During the growth tests in the greenhouse, the ambient temperature and the total daily PPF 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. Nevertheless, the fresh weight, the dry mass and the leaf area, as well as the number of leaves per plant, indicated that the LED lighting treatments were favourable to plant growth during the growth test T1. The quantity and quality of daylight contribution to the total PPF varied according to the weather conditions. Also, the availability of daylight increased during the growth test duration. It is known that the total daily PPF integral is important for the increase of the photosynthetic rate, leaf weight and thickness [64, 65]. Therefore, the increase of daylight availability was more beneficial to the control plants than to the LED-grown plants. Despite the higher daily PPF integral of control plants due to the smaller form factor of the HPS luminaires, the highest fresh weight and dry weight were verified for plants grown under the LED lighting treatment containing red, yellow and blue components (LED2), followed by the red and blue treatment (LED1).

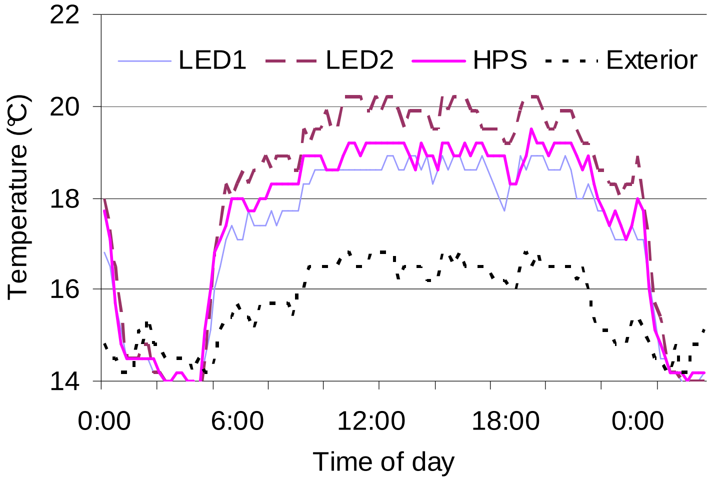


Figure 14 - Typical daily evolution of temperatures at plant-canopy level for LED1, LED2 and high-pressure sodium (HPS) light treatments, and the temperature of the growth room (Exterior) during growth test T1 on February 7th 2005. [VIII]

During T1, the ambient temperature inside the LED2 block was, on average, approximately 1°C higher than inside the HPS block, as shown in Figure 14. This could have been beneficial for LED2 grown plants. Growing lettuce plants at higher ambient temperatures is known to increase the leaf expansion rate, which improves the radiation capture and yield [65]. Thus, the higher dry and fresh weight of LED2-grown plants under 100 to 120 μmol m^{-2} s^{-1} could have been a direct consequence of the higher ambient temperature. On the other hand, other studies have verified that the addition of a small amount of yellow-green light improves the final quality of certain crops including lettuce, suggesting the hypothesis of interdependence between the amount of blue and yellow-green light [66, 67]. In spite of the effects of yellow-green light on crop development, recognition of these effects still is not unanimous or uncontentious [58, 68, 69]. The results of this work also suggest a possible interdependence between the yellow-green and blue light affecting the development of lettuce plants. Although the results suggest that it might be beneficial to use a small amount of yellow light, it is still not totally clear whether the better results obtained with the LED2 treatment in T1 was a direct result of the temperature difference or due to the beneficial effect of the yellow component, or both.

The larger plant population used during the second greenhouse test (T2) was useful to perform solid statistical analysis, which support the viability of use red-orange and blue LEDs as supplemental light for lettuce cultivation. However, mainly due to the different daylight contribution in each light treatment, the results should be evaluated carefully. The higher daylight contribution to the total PPF daily integral under the high-pressure sodium lamps contributed to the slightly higher fresh weight accumulation rate observed for plants in comparison to the LED-grown plants during T2. Moreover, T2 started one month later than T1 during a period of the year characterized by rapid day lengthening and increased frequency of sunny days. Additionally, while the form factor of the LED lumininaires increased almost proportionally with the larger growth area and higher PPF used in T2, the HPS luminaires maintained almost the same form factor. Therefore, the shadowing effect for LED-grown plants was higher, reducing the daylight contribution to the total PPF daily integral and consequently limiting the biomass accumulation in relation to control plants grown under high-pressure sodium. A clear observation of the beneficial daylight contribution on the HPS-grown plants is shown in boxplot diagrams for the fresh and weight of plants in Figure 12 and Figure 13. Namely, the interquartile range, the lowest and highest bounds for the fresh weight and hypocotyl height of HPS-grown plants show that the lighting conditions were more constant for plants grown under the LED systems due to the lower daylight contribution on the total PPF. This situation originated that during the whole experiment lettuce plant samples on the LED-grown plant population were more identical than the samples measured from the HPS-grown population.

The relative amount of daylight contributing to the total PPF on the HPS growth blocks was estimated to be approximately two times higher in comparison to the LED growth blocks. This estimation takes into consideration the size of the luminaires composing the lighting systems and the total horizontal area of the growth block utilized.

Nevertheless, the results of T2 clearly indicate that the use of red-orange and blue LEDs can at least achieve growth performance in terms of biomass production similar 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.

4.1.4 Conclusions

The biometric results indicate that lettuce growth in greenhouse conditions using LEDs as supplementary light to daylight is possible. The results confirmed that the spectrum of the light source is relevant for the crop development, even when artificial light is used as supplementary light to daylight. Growth tests T1 and T2 showed that the bi-spectral component light provided by red-orange and blue LEDs is at least equally effective for biomass accumulation in lettuce plants as high-pressure sodium lamps. Moreover, this can be achieved using approximately 30% less radiant power per unit area than when using high-pressure sodium lamps. This is mainly due to the fact that the LED light spectrum emitted is comprised within the PAR spectral region. In practical applications, greater energy saving performances can be expected for solid-state lighting compared to high-pressure sodium lighting systems if other losses, such as light losses on optical elements of the luminaires, are taken into account.

A third spectral component might also be effective and beneficial in promoting growth under LED illumination. The utilization of yellow with red-orange and blue spectral components provided by LEDs showed a higher fresh weight, dry weight and leaf-expansion rate and the highest number of leaves while maintaining a balanced morphogenesis in the growth test T1. Growth test T1 showed that a trade-off between the blue and yellow components can further enhance the morphogenesis of lettuce. Although the results suggest that the tri-spectral-component LED2 treatment was more effective in promoting plant growth, further experiments are needed to verify the influence of the 1°C higher canopy temperature and the influence of the yellow component.

In spite of the higher fresh weight accumulation of HPS-grown plants during the growth test T2 due to the beneficial influence of the higher daylight contribution, LED-grown plants had the higher dry matter content and showed sturdy growth. HPS-grown plants in comparison with LED-grown plants were delicate and spindly in result of the larger leaf areas, longer hypocotyls and longer leaf lengths.

4.2 Phytotron growth tests

The third and fourth growth tests (T3, T4) were accomplished in phytotron-chamber conditions at the Lithuanian Institute of Horticulture in Babtai, Kaunas District, Lithuania.

4.2.1 Test conditions

During the first growth test (T3) performed in phytotron conditions, a photoperiod of 18 hours light and 4 hours dark with an ambient temperature of 21°C/15°C (day/night) was used to grow lettuce *(Lactuca sativa* cv. 'Grand rapids'). The objective was to investigate the effects of short-wavelength radiation on growth, carbohydrates and nitrate contents of lettuce plants in totally constant abiotic conditions where there was no daylight.

The control plants were grown under special fluorescent lamps spectrally tailored for plant growth. Three LED luminaries with short-wavelength spectral components in UV, blue and cyan regions were used in experiment Exp1, Exp2 and Exp3, respectively. The short-wavelength components accounted, on average, for 8% of the total PPF. The spectra in all LED treatments contained a basal red component with peak emission at 640 nm provided by the red LEDs. This basal component was complemented in Exp1, Exp2 and Exp3 with near-UV, blue and cyan radiation provided by LEDs with peak wavelength emissions at 365, 460 and 500 nm, respectively. The total average PPF was maintained at 200 μmol m^{-2} s^{-1}. [VI] The normalised spectral photon flux distributions of the lighting treatments used during T3 are shown in Figure 15.

During the second growth test (T4) in phytotron conditions, radish *(Raphanus sativus* cv. 'Saxa') were grown in peat substrate with a photoperiod of 16h/8h (light/dark) and constant temperature of 18/15°C (day/night). The aim was to investigate the possibilities of supplementing the light emission of high-pressure sodium lamps with additional spectral components provided by LEDs and to discover the effects of different short-wavelength components on radish growth. [VII]

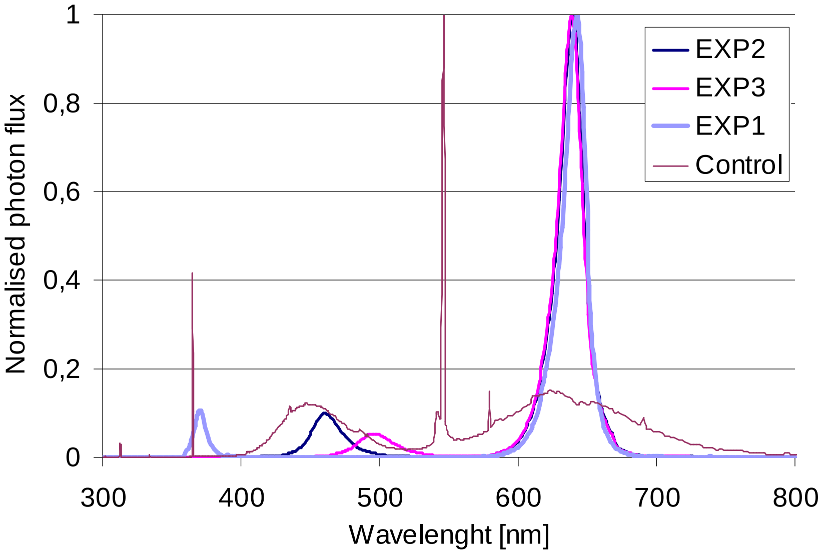


Figure 15 – Normalised spectral photon flux distribution of the LED lighting treatments (EXP1, EXP2 and EXP3) and control lighting treatments provided by special fluorescent lamps (Control) for plant growth used during the growth test T3.

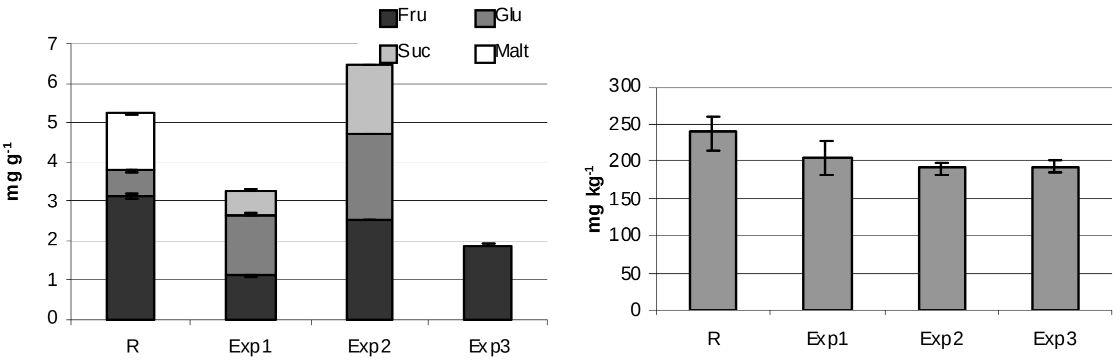
The three complementary lighting treatments (L1, L2 and L3) used during T4 were provided by the same LED spectral regimes used in Exp3, Exp1 and Exp2 of T3, respectively, complemented with light from high-pressure sodium lamps. Approximately 70% of the total PPF in each treatment was provided by high-pressure sodium lamps, while 30% was delivered by the three bi-spectral component LED luminaries, as shown in Table 1. The total PPF was maintained around 225 μmol m^{-2} s^{-1}. Plants grown under the complementary lighting treatments were compared to control plants grown under high-pressure sodium lighting.

Table 1 - PPF spectral composition of the light treatments used in growth test T3 and T4.

Growth test	Light treatments	PPF spectral composition (%)						Total PPF (µmol m^{-2} s^{-1})
		365-nm UV-A LED	460-nm blue LED	500-nm cyan LED	640-nm red LED	High-pressure sodium lamp	Fluorescent lamp	
T3	EXP1	6	-	-	94	-	-	200
	EXP2	-	11	-	89	-	-	200
	EXP3	-	-	7	93	-	-	200
	R	-	-	-	-	-	100	200
T4	L1	-	-	5	66	29	-	227
	L2	4	-	-	67	29	-	223
	L3	-	8	-	64	28	-	222
	Control	-	-	-	-	100	-	225

4.2.2 Results

The results obtained during T3 showed that, in spite of the special fluorescent lamp used, the sturdiest growth was obtained under red and blue LED treatment (Exp2). Cyan radiation (Exp3) enhanced growth of hypocotyl by a factor of two compared to the other treatments (Exp1, Exp2). Lettuce plants grown under red radiation complemented with near-UV radiation component (Exp1) were slight and spindled. The photosynthetic productivity calculation did not show significant differences between treatments after 39 days after germination (DAG), though this parameter was possibly slightly higher in plants grown under fluorescent lamps. The content of chlorophyll *a* in control plants was higher than in all other treatments (Exp1, Exp2 and Exp3).



a) b)

Figure 16 - a) Carbohydrate contents per fresh weight in lettuce leaves 39 days after germination; b) *nitrates content in lettuce leaves per fresh weight.* [VI]

Besides the enhanced nutritional quality resulted from the red and blue LED treatment (Exp2), the nitrates content was also especially lower compared with control plants grown under special fluorescent lamps (R), as shown in Figure 16b.

The most relevant result was observed for carbohydrates content, as shown in Figure 16a. The total concentration of carbohydrates was considerably lower in treatments involving near-UV and cyan light components (Exp1, Exp3) and significantly higher than any other treatment when a blue light component was used (Exp2). Replacing cyan by the blue spectral component has increased the total carbohydrate content by a factor of 3,5. Additionally the use of cyan radiation together with red resulted in plants containing only one type of carbohydrates, fructose.

During the second growth test in phytotron (T4), radish plants grown under high-pressure sodium lamps showed better growth patterns with the largest leaf area and the thickest hypocotyl. Radish in treatments L2 and L3 of T4 were dwarf and slight, and accumulated very little biomass. Meanwhile, plants grown under mixed radiation containing cyan light component in treatment L1 accumulated almost the same fresh weight as the control plants, in spite of having significantly smaller leaf areas and total height than the control plants. All radish plants, including the control plants, did not accumulate biomass in hypocotyls. Therefore, no storage root was formed. [VII]
The content of chlorophyll *a* was significantly higher in control plants. Moreover, the chlorophyll *a/b* ratio in plants grown with complementary LED treatment was lower than that in control plants. The lowest chlorophyll *a/b* ratio of approximately 20% in relation to control plants was observed in radish plants grown under complementary radiation containing a blue light component (L3). [VII]
Similarly to growth test T3, in T4, the most relevant spectral influence was observed on carbohydrate contents and on phytohormone balance of plants. The concentration of abscisic acid (ABA) and zeatin in treatments L1 and L2 were slightly higher than that in control plants and higher by a factor of two in treatment L3. The content of gibberelic acid (GA_3) was lower in treatment L1 but three times higher in treatment L3. Concentrations of the stress hormone ABA were higher in all treatments with complementary radiation, especially in treatment with a blue light component (L3). [VII] However, these dramatic differences between treatments have to be confirmed with further experiments.

4.2.3 Discussion

In the first phytotron growth test (T3), the optimal growth resulted from the LED treatment containing red and blue spectral components (Exp2). However, no significant differences in leaf area, leaf number or biomass production between the treatments were observed. In spite of this, the additional short-wavelength components had a great influence on carbohydrates amount and distribution. The highest concentration of carbohydrates resulted from the red and blue LED treatment (Exp2). The increased content of carbohydrates indicate enhanced vital processes in these plants, since a sucrose metabolism lies at the very heart of the sensitive self-regulatory system of plant development [70]. High total concentration of carbohydrates is one desirable aspect in food quality. However, the quality also depends on the percentage of monosaccharides. This indicates that the control and Exp2 treatments were suitable for lettuce cultivation. Therefore, intensive synthesis of monosaccharides was observed in the lettuce plants grown under these treatments. In addition, substantial amounts of disaccharides, such as maltose in control plants and sucrose in plants grown under red and blue LEDs (Exp2) were found. [VI]

Another positive effect of the spectrally tailored LED lighting treatments was the reduction of nitrates content in comparison with control plants. This effect was of the order of 15 to 20% and was observed for all combinations of red and short-wavelength components under study. This observation is in line with the suggestion that the red illumination component, which is effectively absorbed by phytochrome, plays the key role in the stimulation of nitrate reductase [71] and with the previous observation that supplementation of the red component with blue light promotes the uptake or assimilation of nitrogen in rice plants [72]. [VI]

However, it seems that blue light has also an important role on the potential activity of nitrate reductase. In fact, it has also been reported that, compared to red light, blue light has a higher efficiency in the long-term action of promoting nitrate reductase activity in the early leaf development of radish plants [73]. The discussion as to whether implications of daily nitrate intake are beneficial or detrimental for human health remains a disputed topic [74]. Consumers have been demanding low-nitrate vegetables, which has lead to the creation of legislation by the European Union Commission establishing the maximum nitrate levels for vegetables [75]. However, a few studies suggest several beneficial effects resultant from the intake of nitrate [76, 77].

The results of the second growth test in phytotron (T4) confirmed that light spectrum might be a limiting factor for metabolism and assimilate partitioning in radish. It was previously observed that excessive red light disturbs radish tuber formation and stimulates biomass accumulation in above-ground parts of a plant, instead of its storage tuber formation [78, 79]. The results indicate that the substitution of high-pressure sodium lighting with bi-spectral component complementary lighting in red and short-wavelength regions negatively affected not only tuber formation, but also leaf area formation and biomass accumulation. The resultant light spectrum with high intensity in the red spectral region obviously created stressful conditions for radish growth and development and triggered stress-avoidance responses [80]. The control plants contained similar amounts of fructose, glucose, sucrose and maltose, which reflect normal radish growth. In plants grown under LEDs, the sugar content was dominated by fructose. The content of fructose was 4, 7 and 13 times higher in treatments L1, L2 and L3, respectively. Such distribution of carbohydrates in leaves might be a consequence of disorganized metabolism. The phytohormone concentration results further confirmed the disorganized metabolism of radish plants grown under the complementary lighting treatments. High contents of fructose in radish leaves indicate disturbance in sucrose metabolism, which is typical for the reaction to the exposure of other abiotic stress factors [81]. These results are consistent with phytohormone contents. As carbohydrate partitioning between source and sink organs and tissues is essential for growth and development in higher plants [82, 83], no tuber formation was observed in the cultivated radish. [VII]

Phytochromes, principally thought of as red/far-red reversible pigments, absorb well in the blue portion of the spectrum and are also together with cryptochromes, green light receptors [84]. Therefore, small modifications of light spectrum can initiate responses in phytochrome system. Thus, variation of light intensity in short-wavelength region in treatments L1 to L3 should make a significant influence on the cryptochome system. A positive effect on radish growth has been previously observed [78, 79]. However, this positive effect is obviously not sufficient to counterbalance the negative influence due to excessive red light intensity. Light in the cyan spectral region resulted in slightly improved biometric parameters in comparison with those observed in plants grown under with short-wavelength components in blue and UV regions. There are some previous reports on the positive effect of green light for plant cultivation [59], thus it is possible that cyan light, being closer to the green region, has the same biological effect. [VII]

The lower chlorophyll *a*/*b* ratio observed on plants grown under complementary LED lighting treatment in comparison with control plants is an indication of decreased activity of their photosynthetic system. [VII]

4.2.4 Conclusions

Possibility of intentional monitoring of the trade-off between quantity and quality of sugars by selecting the light spectrum is worthy of further detailed study. This feature might be of practical importance for the food industry and beneficial for consumers of vegetable crops such as lettuce. The combination of red and blue light components was found to be favourable for lettuce growth. In spite of the development of plants cultivated under light at this spectral composition was similar to the development of control plants grown under special fluorescent lamps, the nitrates content was lower and the production of carbohydrates was higher and more balanced. The results of growth test T3 indicate that an optimized lighting treatment that can lower the nitrates content of leafy green vegetables, such as lettuce and radish, seems to be possible with LED-based lighting.

Growth test T4 showed that the complementation of high-pressure sodium light with short-wavelength components provided by LEDs is not sufficient to promote the healthy growth of radish plants. The increase of red light (600 - 700 nm) from approximately 40% to 80% of the total PPF, could have been excessive. Moreover, none of the bi-spectral component complementary LED lighting treatments had a crucial influence on radish development, though the regime containing the cyan component was more favourable for biomass accumulation than the other shorter wavelengths. Lighting with another spectral composition is needed for healthier growth of radish under artificial lighting.

5 The phyllophotometric system

5.1 Introduction

Solid-state lighting is viewed with increasing interest and expectations for horticultural lighting also. However, in practice, it 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. 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 [85-91]. The actual situation in measurements of radiation used by plants in photosynthesis is confusing. Different metrics are frequently and indiscriminately used to quantify radiation for plant growth. Radiometric, quantum, phytometric and photometric units are used to quantify and report photosynthetic radiation. The phyllophotometric system is a new proposal for systematization of radiation measurement used by plants in photosynthesis. [IX]

5.2 Definition

Phyllophotometric is the name for the new system and comes from the Greek words '*fyllo*', '*fotos*' and '*metrikos*' which denote '*leaf*', '*light*' and '*metric*', respectively. The phyllophotometric system is based on the quantum or photon system by considering 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 definition of the phyllophotometric system was achieved in a manner analogous to that of the CIE system of physical photometry [92]. The main quantity, the phyllophotometric flux (ϕ_{ps}), is 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 relative quantum efficiency spectral curve determined by McCree, replicated by Inada, and later refined by Sager [93-95]. The phyllophotometric flux ϕ_{ps} has as its unit the 'phyton' (pt) and can be derived using the following equation

$$\phi_{ps} = K_y \int_{\lambda=300nm}^{\lambda=800nm} \phi_{p,\lambda} P_y(\lambda) d\lambda \tag{7}$$

where, $P_y(\lambda)$ represents the relative quantum efficiency spectral curve.

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:

$$\phi_{ps} = K_y \int_{\lambda=300\,nm}^{\lambda=800\,nm} \frac{\lambda}{N_A \times h \times c} \phi_{e,\lambda} P_y(\lambda) d\lambda \qquad (8)$$

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 a vacuum (2,998 × 10^{8} m s^{-1}) and λ the photon's wavelength in meters (m).

5.3 Evaluation and discussion

In order to understand the usefulness of a coherent metrics for photosynthetic radiation, hereafter a comparative study is made between conventional 400-W high-pressure sodium lamp and a bi-spectral component LED lamp composed of power red and blue LEDs.

An important aspect of horticultural lighting is the electro-optical performance of the light sources used. The efficacy value of the different measurement systems gives, to a certain extent, an indication of the energy-efficiency performance. Efficacy is commonly defined by the ratio of the output flux of the light source to the input power.

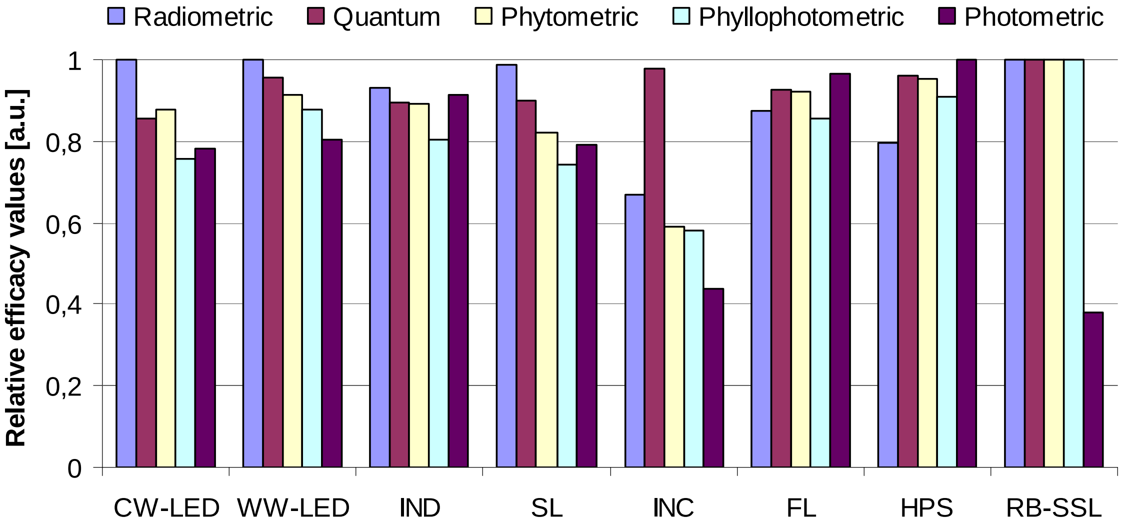


Figure 17 - Comparison of relative maximum efficacy values of different light sources by using different measurement systems. [IX]

Figure 17 compares the relative maximum efficacy values of a bi-spectral component LED lamp composed of power red and blue LEDs (RB-LED), cool-white phosphor converted LED (CW-LED), warm-white LED (WW-LED), induction (IND), sulfur (SL), incandescent (INC), fluorescent (FL) and high-pressure sodium (HPS) light sources. The radiations of these sources are evaluated by the different measurement systems considering an electrical-to-optical energy conversion efficiency of 100%. It can be verified that spectrally tailored light sources such as the red and blue LED lamp offer the highest energy saving potential.

Table 2 - Comparison of light costs between high-pressure sodium (HPS) lamp and bi-spectral component LED lamp composed of power red and blue LEDs (RB-LED), taking into account real operation in plant-growth conditions. [IX]

	HPS	**RB-LED**
Phyllophotometric efficacy [μpt W^{-1}]	91,7	87,3
Lifetime [hours]	10 000	30 000
Phyllophotometric flux [mpt/lamp]	38	38
Input power [W/luminaire]	414	435
Lamp cost [€ mpt^{-1}]	685	23 711
Lamp cost [€]	26	900
Capital cost [€ pt^{-1} h^{-1}]	0,070	0,791
Operating cost [€ pt^{-1} h^{-1}]	0,872	0,917
Ownership cost [€ pt^{-1} h^{-1}]	0,942	1,708

To evaluate the overall of the light sources, the losses due to optics were considered. A wider evaluation includes also the light costs. Table 2 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 performances. This level of depreciation value is typical in LED-based luminaires using common and low-cost passive cooling solutions. The lifetime of power LEDs are commonly defined at 30% or 50% light depreciation. However, for plant-growth applications, one of the main manufacturers of lamps for plant growth recommends the replacement of high-pressure sodium lamps when the light depreciation achieves 15% and 10% due to economic reasons. The so-called "*service lifetime*" for high-pressure sodium lamps is equivalent to approximately 10 000 hours of operation, while, for high-brightness red and blue LEDs, 30 000 hours or higher can be reached. Due to the inherent losses in the optical elements of the luminaires, the total phyllophotometric flux of the high-pressure sodium lamp was obtained considering 60% luminaire efficiency. For the LED luminaire, 90% efficiency 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 light sources and drivers. The ownership cost results from the sum of operating costs and capital investment costs [96]. The results show that one of the aspects delaying the uptake of LED technology in horticultural lighting is the high capital investment cost, which is more than 10 times higher than the one required 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 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 [97]. At this pace, and considering the previous comparison it would be expectable that the ownership cost of a similar type of red and blue LED lamp will be similar to the ownership cost of conventional high-pressure sodium lamp by the year of 2010. [IX]

5.4 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. [IX]

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. Therefore in our future research the phyllophotometric system will be further developed and practically tested in order to further improve certain aspects such as the ones hereafter briefly discussed.

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 crop. [IX]

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 measurable 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. [IX]

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 [92]. 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. [IX]

6 Concluding remarks and future aspects

The optimization of electrical energy conversion into usable photosynthetic energy to be used by plants is achievable through versatile control of the quantity and quality of the radiation. LED-based luminaires allow wide control of light spectrum and intensity, important factors in plant growth. Plants are sensitive to minor changes in the spectral composition of the radiation. The results obtained from the experiments performed corroborate this fact. The growth results of plants grown under LEDs were dependent on whether the LEDs were used as a whole substitution of daylight or whether they were used as a supplemental or as complementary lighting solution. The effects of the light spectrum of supplemental LED lighting on growth rates and in the morphology of lettuce plants are likely to be less when the availability of daylight is greater.

In addition to supplemental lighting, LEDs can also be used as complementary lighting of conventional light sources. The complementation of conventional light sources should be achieved carefully. LED luminaires with optimised spectral composition for plant growth in phytotron conditions may not achieve identical growth results when used to complement other light sources with different spectra. In addition, different crops may require different light spectra for optimal development and quality. The generation of tailored spectra for specific crops is another important advantage of LEDs over conventional light sources.

There is now the possibility that LEDs can be utilized in new ways in horticultural lighting, although certain aspects of their use related plant responses to light quality and quantity are still under investigation. The interaction between the known and unknown photoreceptors and their specific roles in mediation of physiologic responses requires additional investigation. The inclusion of a third spectral component in yellow to a bi-spectral-component LED luminaire composed of red and blue LEDs has given an indication that further optimization of plant growth is possible. This can also indicate that additional interactions mediated by the known or unknown photoreceptors may exist in other spectral regions.

Lettuce plants grown under LEDs in phytotron conditions showed sturdier growth indicating improved nutritional quality in terms of carbohydrates and lower nitrate contents than plants grown under specially developed fluorescent lamps for plant growth. The high nutritional value, low contents of nitrates and improved morphogenesis of LED grown crops are promising indicators, which may respond to the demand for high-quality products by consumers.

Energy efficiency is nowadays a hot topic worldwide. LEDs are potentially energy efficient light sources. In Finland the amount of energy used in year-round crop production in greenhouse environment was approximately 2 000 GWh, representing 0,5% of the total consumption of energy in 2004. Approximately 20% of the energy consumed was used mainly used for lighting. This represents 5% of the total electricity consumption due to lighting in Finland. Therefore, efficiency, and, more specifically, production efficiency plays an important role in the horticulture crop production industry in greenhouses. High crop yields with reduced production cycles and with the lowest possible production costs are important rules governing this industry and can be optimized also through lighting. In commercial year-round crop production, the costs due to supplemental lighting can reach in some cases 1/3 of the total production costs. The energy efficiency potential offered by LED technology may further reduce the economic and environment burden due to lighting and increase yields, resulting in improved production efficiency. The potential energy efficiency of LEDs may in the future practically represent important reductions on the electrical consumption in greenhouses and consequently on the CO_2 emissions of the year-round crop industry. If the light sources used in the greenhouses installations in Finland in 2004 were retrofitted with LEDs with similar electrical efficiency, the lower optical losses of LED luminaries could allow reducing the electricity consumption in approximately 20% to 30%. This savings would reduced the CO_2 emissions in approximately 22 000 tonnes for that year. However, the design of efficient LED systems for plant growth should not only take into account the conversion efficiency between electrical and radiant energy, but also the conversion efficiency between the radiant energy and chemical energy, which is ultimately used by plants for production of biomass. While the first aspect is mainly dependent on the characteristics of the semiconductor material and internal structure of the LEDs and appropriated circuit topology of drivers, the second one depends mostly on the spectrum of the light source used. Due to control flexibility of LEDs, the overall system efficiency and growth control can be further enhanced by integrating and optimization the light quality and quantity with all abiotic parameters important for the crop development.

The economical viability of solid-state lighting installations for plant growth is evolving favourably in relation to conventional lighting installations. Although the actual high price of LEDs is a negative factor influencing the final ownership cost of LED luminaires in comparison to high-pressure sodium lamp systems, the long life expectancy is a beneficial one. The life span of an LED installation can be two to three times longer than a conventional HPS-based one. Considering 80% to 90% as the minimum light depreciation value recommended for economically viable horticultural lighting installations, the potential total useful lifetime for LED installations would be approximately eight years. This is based on utilization of supplemental lighting during five to six months per year with a photoperiod of 20 hours light. Nevertheless, the reliability and safety aspects of solid-state lighting installations for plant growth have to be further investigated. One of the main factors affecting the operational reliability of LEDs in plant growth in controlled environments may be the high humidity content. Humidity can accelerate the degradation of the semiconductor alloys if the encapsulation isolation is not effective. Current standard wet high-temperature operating life tests carried out by LED manufacturers are limited to 1000 hours. However, 1 000 hours might not be enough to allow conclusions to be drawn as to the effects due to longer term exposure to humidity.

The future retrofitting of conventional luminaries by LED luminaries is strongly dependent on the costs and on the technological development pace. However, most probably, future applications in commercial plant-growth facilities will continue to be ruled by economics and productivity. Therefore, the cost of photosynthetic radiation of LED luminaires is one of the main factors to be considered. Nowadays, the higher purchase cost of LEDs is the main reason for the higher ownership costs of LED luminaires in comparison with conventional lighting systems such as high-pressure sodium light luminaires. The forecast evolution of prices and light output are clearly beneficial for LEDs.

A reliable evaluation of the photosynthetic performance of solid-state lighting systems and its costs depends on the metrics used to quantify it. Photons with different energies have different photosynthetic effectiveness. The existing measurement systems used to quantify radiation utilised by plants in photosynthesis weight photons differently. The most proper way to measure radiation in plant-growth applications in future should improve the measurement accuracy and address the interoperability between the existing measurement systems and thereby serve as a useful tool in comparing light sources for plant-growth applications. Moreover, if the photosynthetic capability of a light source is to be quantified, then the nature of its actinic response should also be considered. The establishment of a new measurement system to quantify radiation in plant growth will allow a more appropriated design, characterization and optimization of future lighting installations for plant growth. Also, in terms of economics, it is expected that a coherent metrology will better forecast and correlate investments in lighting with the expected and desirable benefits. The future research will be directed towards improvement and testing of the phyllophotometric system in order to coherently address the previous referred issues.

The photosynthetic rate of plants is dependent on the daily radiation integral provided. The typical photosynthetic photon fluxes commonly used in supplemental lighting require the utilization of LEDs with optical emission output. It is clear that plants have responses to optical radiation that are different from those of humans. New solid-state lighting installations for plant growth will provide light at spectral regions that can significantly differ from conventional lighting systems tailored for human vision. The possible effects of this kind of lighting environment on personnel working in such an environment are, however, not yet known.

The utilization of LEDs may contribute to the improvement of production efficiency and it will also have its effects on the preservation of the natural environment. However, further studies have to be performed in order to clearly verify and quantify the benefits attained on the preservation of nature by producing quality vegetables and ornamental plants locally and year-round.

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