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PHOTOBIOLOGICAL ASPECTS OF CROP PLANTS GROWN UNDER LIGHT EMITTING DIODES

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ABSTRACT

The steady development of the light emitting diode (LED) technology over the years has led to an increasing number of new related applications. The present paper gives an overview of the photobiological and physiological aspects of crop plants grown under LEDs. The photosynthetic potentialities of LED-based light sources in future applications such as in greenhouses are discussed. LEDs can allow full control of the light sources spectra, which can be used to control the development of pathogenic diseases and to improve morphologic characteristics of the crop plants. Computerized management can easily include and fully integrate the control of several important aspects for a better development of a specific crop. Such aspects are for instance light spectrum, quantity, photoperiod, photoregime, distribution and supplementation, together with temperature and CO_2 concentration.

Keywords: Light emitting diodes, photosynthesis, photobiology, PAR, crop plants

1. INTRODUCTION

The potentialities of LEDs as a photosynthetic radiation source for plant growth has been evaluated and confirmed in the early 1990's [1]; [2]. Applications in confined environments have showed the viability of LEDs in bioregenerative life support systems and food production in long missions in space [3]; [4]. Also on the Earth, the production of crop plants in greenhouses is one of the areas where the substitution of the common artificial light sources by LED arrays might bring some significant benefits. The spectral characteristics of the narrow-band LED, which can closely match with the absorption peaks of the chlorophyll molecules, is one important feature to be taken into account. Additionally, narrow-band LEDs give the possibility of creating a specific spectral distribution for determined crop specie, in order to achieve a certain effect on the plant growth. Thus, it is important that the photobiological aspects as well as the physiological responses resulting from the plant illumination with narrow-band LEDs are properly understood.

2. PHOTOBIOLOGICAL ASPECTS

Photobiology is a branch of biology, which deals with the effects of light on living organisms. Photosynthesis is one of the most important topics of photobiology studies in plants. Plants use photosynthesis to convert the radiant energy of the light into chemical energy. This energy is then used by molecules, for biomass production and as a source of information. The information gather from the radiation is an important factor influencing the circadian rhythmic and metabolic cycle of the plant. Although the basic chemical reaction equation of photosynthesis looks quite simple, in practice photosynthesis is a rather complicated photochemical process, which involves several sets of reactions. The laws of photochemistry can generally express the way that plants harvest light. One of the most important laws for photosynthetic organisms states that light propagates as waves but interacts with matter as particles (e.g. quanta of radiant energy or photons).

Photobiological effects or responses may happen when a quanta of light is absorbed by a photoreceptor or photopigment. The efficiency with which absorbed photons of different wavelengths are participating in the photosynthesis process is represented by the relative quantum efficiency curve shown in Figure 1 [5]. Based on that, the photosynthetically active radiation (PAR) boundaries have been defined to comprise the wavelengths between 400 and 700 nm [6]. Nevertheless, those limits are not yet of general acceptance because the average action spectrum of plants can go behind those boundaries, which may contribute and influence for plant growth. Recently, a new concept of light measurement for plants using extended PAR (320 – 780 nm) has been proposed [7]. The phytometric system, as it is named, is based on the RQE curve by analogy with the photometric system, which is based on the average spectral sensitivity of the human eye, represented by the V(λ) curve. This system tries to address the problem of interconversion between the existing light measurement systems. Nevertheless, in research work, quantum system still is the most common light measurement system. This results from the fact that the amount of photosynthetic photons incident on a plant leaf can be directly related with the amount of chemical change in molecules (Stark-Einstein law of photochemical equivalence). Hence, photosynthetic photon flux (PPF) in μmol m^{-2} s^{-1}, is used for quantification of the photosynthetic radiated energy incident on the plant leaf surface per unit of time. Also here the quantum system units are not unanimously accepted, thus photometric and radiometric units are often found in literature related with plants. In manufacturers' data sheets, photometric units are often given, where the total luminous output in lumens (lm) and the luminous intensity in millicandela (mcd) are often found. There, conversion factors are needed in order to have the quantum or radiometric equivalent. This process may be sometimes troublesome and may conduct to unwanted errors or inaccuracies.

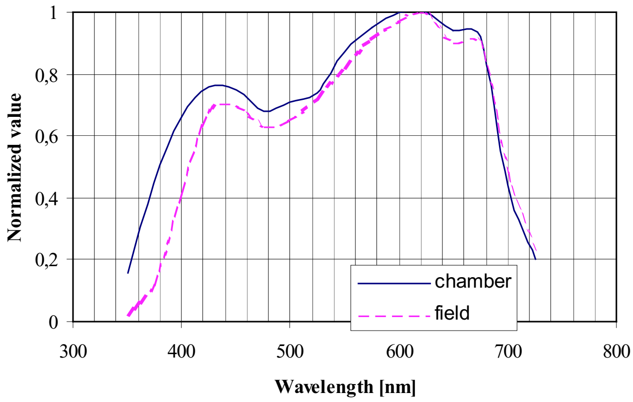

Figure 1. - Relative quantum efficiency curve (RQE) for chamber and field grown plant species [5]

The non-linear response of the plant to the incident radiation on the leaves is due to the existence of large variety of photopigments (also called photoreceptors). These photopigments have their own characteristic action spectrum and sensitivities. Photopigments can be found in at least three known photosystems, which are the photosynthetic, phytochrome and cryptochrome or blue/UV-A photosystems. In the photosynthetic photosystem the existing pigments are chlorophylls and carotenoids. Here, the quantity of light or the amount of PPF is the most significant aspect, since the activity of those pigments are most closely related to the harvest of the radiant energy within their own action spectrum. The physiological importance of phytochromes has been widely investigated [8]; [9]. Phytochromes exist in two interconvertable forms, which have their sensitive peaks in red (660 nm) and in far-red (730 nm) regions, respectively. Photomorphogenetic responses mediated by phytochromes are usually related with the sensing of the light quality through the red (R) to far-red (FR) ratio (R/FR). As an example, low R/FR ratio results on leaf expansion and promotion of stem elongation while high values may inhibit it. The photo-reversibility, which characterizes phytochrome, is also dependent on the PPF used. This means that depending on the irradiance level, photomorphogenetic effects mediated by phytochromes can vary. Blue/UV-A pigments are found in the cryptochrome photosystems, which are involved in several different tasks, such as monitoring the quality, quantity, direction and periodicity of the light. Blue light is also directly related to morphological responses found in crop species such as Lettuce (*Lactuca sativa* 'Grand Rapids') and Pepper plants (*Capsicum annuum* 'Hungarian Wax') [10]; [11]. The increase of the number of blue photons was required to reduce the length of the stem and increase leaf thickness in Pepper plants and hypocotyls and petioles of Lettuce seedlings.

Photomorphogenesis is more dependent on the spectral distribution of the light source than on the PPF level. 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 at the far-red region (700 - 800 nm)

[12]. Despite their relative lower magnitude, the photobiological responses can be important in terms of enhancement of the growth and development of the plant. Although radiation of wavelengths below 300 nm can be highly harmful to the chemical bonds of molecules, plants can absorb radiation also in this region. Plants grown in chambers tend to use a higher percentage of UV-A photons than field-growth plants as it is shown in Figure 1. Moreover, blue-light 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 [12]. The different groups of blue/UV-A photoreceptors have important effects for the development of the plant, such as germination, stem extension, leaf expansion, root growth and phototropism. Therefore, it would be useful to know in which way those interactions occur, and their relation to other radiation wavelengths in yellow, green, red or far-red regions. This knowledge, together with the determination of maximum and minimum thresholds required from each one of the wavelength involved, is needed in order to allow a normal development of the crop grown under LEDs or even enhance it. Furthermore, photomorphogenetic effects would be better predicted and easier controlled by using an appropriated spectral distribution.

3. FUTURE RESEARCH

The advent of the LED technology has enabled a sort of reinvention of photosynthesis. If the actual trend in LED technology development is maintained, as it is predicted to happen, solid-state lighting can bring some very beneficial developments to horticulture industry. Some of these future developments and our future related researches are discussed below.

As it is with common light sources, LEDs can also be used in greenhouses to partly or totally supplement the daylight. Small increase in the irradiance level of supplementary lighting during the wintertime in Norway increased the yield of cuttings in 49% and 58 % for *Begonia* and *Chrysanthemum* respectively [13]. Also the redistribution of the radiation can be done in a more flexible way with LEDs due to their compact size and the numerous possibilities of luminaire designs. The redistribution of direct solar radiation in greenhouses has been estimated to give an increase of 22% in annual productivity even if this results in lower light intensities over the leaf [14]. The distribution of artificial light can be more easily done with LEDs than with the traditional light sources due to their small dimensions and optical characteristics. Therefore, light distribution strategies in greenhouses using LEDs may also result in an increase of the crop production, even if the total PPF is lowered. The low PPF can be compensated with a longer photoperiod and/or higher CO_2 concentrations, as it has already been successfully demonstrated with Lettuce (*Lactuca sativa* ‘Summer-green’) [15]. Besides the photoperiod, the photoregime can be a useful tool to enhance the growth and development of the plant. It is known that photoregimes that contemplate light pulses or fluctuating lighting increase the efficiency of light usage by plants [16]. Photoperiod and lighting regimes implementation can easily be achieved with LEDs due to their flexibility of control. Important factors to be considered are for instance, array design, control strategies, application *in loco* and the actual LED technology’s state of development.

The advantages of using LED-based light sources are not limited to control of physiological aspects of the plant growth, such as photosynthesis or photomorphogenesis. Another important feature of the spectral quality control is the interference with the development of pathogenic diseases on plants [17]. The interactive effects of multiple narrow-bandwidth wavelengths and the evolution of pathogens diseases under different spectral regimes are of paramount importance and need further investigation.

LED-based light sources for crop production allow full control of one of the most important factors in the plant growth, which is light. The photosynthetic performance of the light system can be enhanced if a full integration in the computerized management environment of the greenhouse is done. The control flexibility of LEDs can allow free adjustments of the light characteristics in terms of wavelengths (light quality), PPF level (light quantity), photoperiod and photoregime together with ambient temperature and carbon dioxide (CO_2) concentrations.

The photosynthesis is today an actual and wide topic under research. Some of the photobiological response mechanisms are not totally understood. A more accurate understanding of the photobiological effects and mechanisms and their relation to the spectral quality of the light is still needed. A good example of this can be found in the green range (500 – 600 nm) of the PAR where yellow is included (580 – 600 nm). Although the green color of the leaves is due to the inability of chlorophylls to absorb green photons, it seems that yellow light may contribute to the plant growth in the majority of crop species [18]. Nevertheless, the continuous acquisitions of new concepts and knowledge in the plant photobiology and physiology, complemented with the fast development of LED technology, make the application of solid-state lighting irreversible in greenhouses and in growth rooms for crop production.

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