Life Sciences in Space Research 15 (2017) 18–22

Contents lists available at ScienceDirect

Life Sciences in Space Research

journal homepage: www.elsevier.com/locate/lssr

Whole high-quality light environment for humans and plants

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ARTICLE INFO

Keywords:
Photosynthetically active radiation
Yield photon flux
Phytochrome photo-equilibria
Correlated color temperature
Color rendering index

ABSTRACT

Plants sharing a single light environment on a spaceship with a human being and bearing a decorative function should look as natural and attractive as possible. And consequently they can be illuminated only with white light with a high color rendering index. Can lighting optimized for a human eye be effective and appropriate for plants? Spectrum-based effects have been compared under artificial lighting of plants by high-pressure sodium lamps and general-purpose white LEDs. It has been shown that for the survey sample phytochrome photo-equilibria does not depend significantly on the parameters of white LED light, while the share of phytoactive blue light grows significantly as the color temperature increases. It has been revealed that yield photon flux is proportional to luminous efficacy and increases as the color temperature decreases, general color rendering index R_a and the special color rendering index R_{14} (green leaf) increase. General-purpose white LED lamps with a color temperature of 2700 K, $R_a > 90$ and luminous efficacy of 100 lm/W are as efficient as the best high-pressure sodium lamps, and at a higher luminous efficacy their yield photon flux per joule is even bigger in proportion. Here we show that demand for high color rendering white LED light is not contradictory to the agro-technical objectives.

1. Introduction

In conditions of long-term space travels, growing plants can provide spacemen with food and vitamins (MacEloy, et al., 1992). Placing plants in separate plant growth units is one of two obvious approaches. An alternative approach to place plants in the same vital spaces where the crew is located has an obvious advantage: improvement of the life quality and the level of psychological comfort of spacemen. Plants themselves have a significant decorative function. In addition, a union space occupied by humans and plants will increase a scarce volume of the visually observed light-saturated space for humans, at least optically.

The unification of the plant and human light environment requires the energy-efficient solution, taking into consideration the plants requirements in the spectral components and human requirement in the light of high quality.

Plants need intense light, and therefore energy efficiency is important. The light most efficiently used by plants is red light (McCree, 1972). However, the studies (Hoenecke et al., 1992; Tripathy and Brown, 1995) show that under narrow-band red light alone, plants do not develop well; for the synthesis of chlorophyll and vegetative growth, blue light should be added to red light. The papers (Ptushenko et al., 2015; Folta and Maruhnich, 2007; Zhang et al., 2011) convincingly demonstrate that green light has both energy and regulating functions, and that the narrow-band red and blue light in some cases inhibits the plant growth. The study (Kim et al., 2004) shows that the addition of green light to a red and blue spectrum significantly increases the yield of lettuce. The study (Lin et al., 2013) shows that adding white LED light that fills a gap in the green region to red and blue light improves the appearance and taste of salad.

Currently, white LED light with additional red light is more promising light spectrum for increasing the efficiency of plant photosynthesis (Urrestarazu et al., 2016). But there is evidence that changing of the red light share in the incident photon flux at a typical irradiation intensity, at which the yield of biomass is proportional to the intensity of illumination, did not have a significant effect on the yield (Avercheva et al., 2016). Consequently, adding red light to the white LED spectrum is advisable for increasing the color rendition. But it is not necessary to add red light in excess, giving the white light pink color hue. Energy-efficient light for plants can be white.

The experimental study of salad, radish and pepper (Cope et al., 2014) shows that the plant development is not dependent on whether you are using a continuous or a narrow-band spectrum. In particular, the replacement of a fluorescent tube, red and blue, and red, blue and green LEDs by white LEDs with the same illumination intensity and proportion of blue component did not affect the development of the plant. Consequently, the development of the plant is determined by the balance of the main spectral components; delicate features of the spectrum are not important. Light for plants can have a spectrum of different shapes, including those designed for human vision.

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http://dx.doi.org/10.1016/j.lssr.2017.07.001
Received 26 March 2017; Received in revised form 30 June 2017; Accepted 1 July 2017

The research objective is to compare the efficiency of supplementary plant lighting by as many general-purpose white LED lamps as possible to the supplementary lighting efficiency of traditional industrial gas-discharge high-pressure sodium phytolamps (HPS) in the known metrics. Concomitantly, this work identifies the main biologically active components of white light such as phytochrome photo-equilibrium φ, proportion of phytoactive blue light, and yield photon flux (YPF) and their dependence on the correlated color temperature (CCT) and color rendering index (Ra and R14). Lastly, we show that the demand for high color rendering white LED light is not contradictory to the agro-technical objectives, but conversely, this work examines if it is energetically appropriate to improve the quality of a white light environment for both humans and plants.

2. Methods

2.2. Investigated sources

The only type of white light sources comparable in energy efficiency with HPS are LEDs. It was analyzed a statistically significant number — 205 spectra of LEDs Cree xp, ml, mpl mx, xt, xhp, mhb and cxa series; Osram Oslon series, Nichia 757 and 219 series, Philips rebel series, Seoul Semiconductor 5630 and 3030 series, LG 5630 series, Samsung 5630 series, Sitizen 353 and 303 series, Everlight 5630 and 3528, Edison EdiPower HM series, SemiLEDs ev series and some others. Sources of information on the spectra: officially published documentation on the LEDs and the information from the representatives of manufacturers. We have examined typical spectra of white blue-pump LEDs consisting of a narrow blue peak at the wavelength close to 450 nm and a broad green-yellow component (Fig. 1). These LEDs are used in the majority of general-purpose LED lamps.

LED sources are compared with reference HPS lamps according to YPF values. In all calculations, the standard spectrum CIE HP1 (CIE, 2004), the closest among other CIE standard spectra to the spectrum of a popular HPS lamp Philips MASTER GreenPower CG T 600W, is used as an HPS spectrum (Fig. 2).

2.3. Spectrum occupancy degree

For white light, the spectrum completeness degree can be indirectly estimated by the international standard color rendering index Ra provided by the Commission Internationale de L'Eclairage (CIE) CRI metric. The higher R_a, the greater the occupancy of the spectrum and the lower its differences from a natural light source (Fig. 1a). The study included the white light spectra with a general color rendering index R_a of 64 to 98.

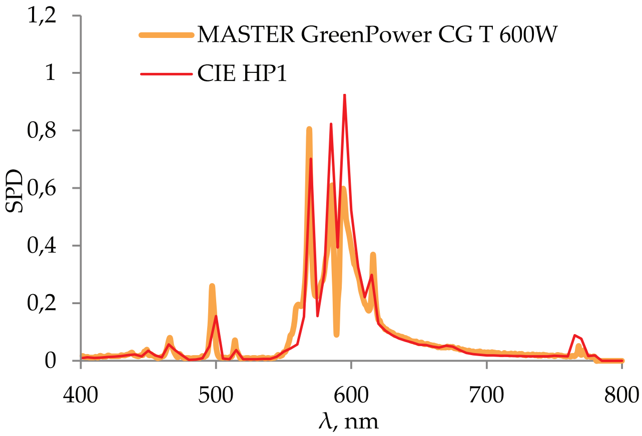

Fig. 2. Spectral power distribution CIE HP1. Spectral power distribution HPS Philips MASTER GreenPower CG T 600W is given for reference.

2.4. Chromaticity

The parameter that characterizes the balance of the main white light components most roughly, i.e. by the ratio of red and blue components, is the correlated color temperature (CCT) (Fig. 1b).

The white light spectra with color temperatures of 2700–6500 K have been studied (Fig. 3). Slight deviation of the chromaticity coordinates from the black body curve has been allowed within ANSI C78.377-2008 tolerances.

2.5. Red light response

The ratio between energy shares of near and far red light in the spectrum affects the balance of phytochrome forms Pf and Pfr in a leaf and is numerically determined by phytochrome photo-equilibrium — φ determined using the formula (Sager and McFarlane, 1997):

$$\phi = \left[\sum_{300}^{800} N_\lambda \sigma_r\right] \div \left[\sum_{300}^{800} N_\lambda \sigma_{fr} + \sum_{300}^{800} N_\lambda \sigma_r\right]$$

There N - the number of photons; phytochrome photochemical cross sections σ_r - red absorbing state, σ_{fr} - farred absorbing state.

In nature, this ratio depends on whether the plant is shaded by leaves of other plants, and for different plants at various stages of development determines different physiological effects. The main responses are shade-avoidance syndrome, seed germination, de-etiolation of seedlings, and impact on photoperiodism (Wareing and Phillips, 1981). φ value varies from 0.04 under a dense leaf layers canopy to 0.54 under typical sun light (Smith and Holmes, 1977).

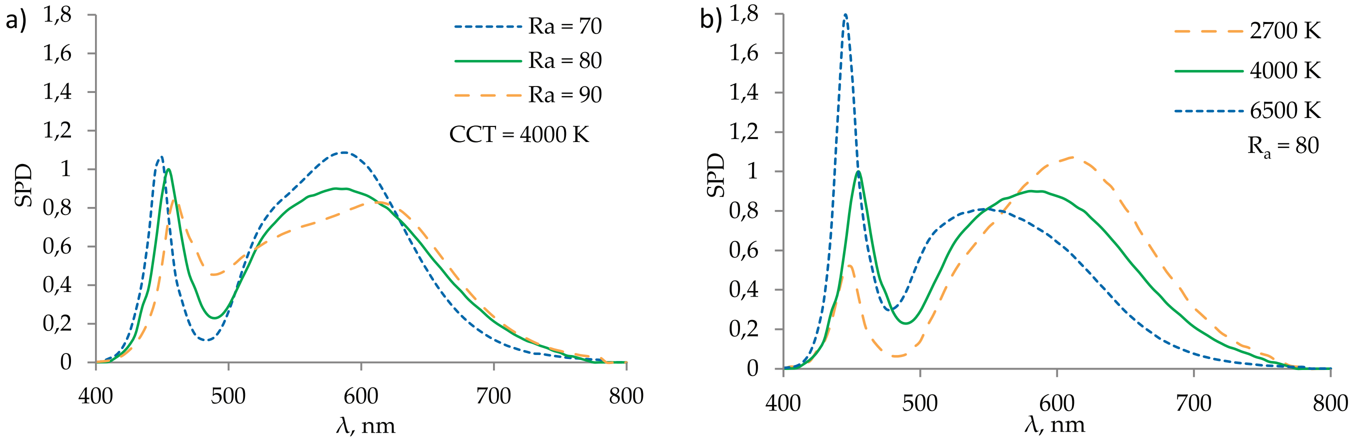

Fig. 1. The shape of the spectrum a) different general color rendering index; and b) different balance of a short-wave and long-wave component determined by the color temperature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)