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Energy-efficient LED irradiator for greenhouse cropping

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Abstract. The paper presents the results of modeling and calculation of highly directional optimal light intensity curve (LIC). The authors proved the effectiveness of using the calculated LIC for lighting of greenhouse plants. A method for placing fixtures with LIC in a typical greenhouse was recommended

1. Introduction

Ideal conditions for plant development at any time of the year in any region of the earth can be created in the greenhouse. Constantly increasing scale of this mode of production of agricultural products, the need to improve the productivity of greenhouses requires introduction of new technologies, including those for supplementary lighting of plants. This became possible after the development of high-power LEDs that make possible to design irradiation facilities (IF) of different radiation spectra and to provide the control of exposure parameters.

Many researchers note the advantages of LED irradiation, and manufacturers are working intensively to create special LEDs and irradiators for greenhouse IF [1–4]. The basic principles of the energy-efficient IF for greenhouses are reported in [5]. In this paper, we present the results that allow more specific requirements for the parameters, design and radiation spectrum of a universal adaptive irradiator for supplementary lighting of various kinds of plants cultivated in greenhouses. The optimal requirements to radiation sources for plant growing were as follows:

– proper plant development requires the irradiation well balanced in spectrum and flux in the range of 380–750 nm.
– plants are adapted to the quality and flux of the light under which they formed.
– the requirements for radiation quantity and quality may vary during plant development.

Consequently, the irradiator for supplementary lighting of plants should provide the required reference radiation spectrum and the possibility of its variation. The irradiator design should be convenient for its installation and operation, and provide admissible fluxes and their uniform distribution across the area (volume) of the irradiated plants.

IF is to be adaptive to seasonal, daily, hourly, and continual changes in solar radiation parameters and changes in the quantity and quality of the radiation required for plant development.

2. Experimental methods

The main objective when designing the adaptive LED IF is the choice of the reference radiation spectrum through selection of LEDs emitting in different spectral regions. Selection of the emission spectrum is typically associated with the action spectrum of photosynthesis in plants [6-9]. N.N. Protasova, the author of the most frequently referred research [10], defined the "optimal" ratio of the radiance (W/m2) for plants for the wavelength range (nm): 400–500/500–600/600–700 equal to 30/20/50, respectively. The reference spectrum can be changed by variation of the LED current.

As it was shown in [5], the optimal and variable ratio in the LED module radiation spectrum can be created from various combinations of colored and white LEDs. With respect to the action spectra of photosynthesis and photomorphogenesis, the optimal and universal irradiator is a three-color version: white (warm color), blue (λp=420–465 nm) and red (λp=660 nm). Three types of LEDs allow change in the total flux, and simultaneously they can be used to create any combination of the spectrum.

White LED is the basis for creating a reference spectrum. It covers a wide spectral range and can provide excitation of all pigments which cause the photochemical processes in plants, including the photocontrolling one. The latter requires significantly less light energy compared to photosynthesis. The LED Nichia NS3W183TS, which has the widest spectral range (420–750 nm), is most suitable for this purpose.

For energy-intensive photosynthesis and control of photochemical processes in the plant, white LED should be mixed with blue and red LEDs. The blue LED Nichia NCSB119T is suitable for this purpose. The PHILIPS LED LXM3-PD01 can be used for the red spectral region.

The ratio derived by N.N. Protasova was taken as a criterion to select the number of white, blue and red LEDs in the irradiator. The SPECTRA software was used for LED selection [11]. We found that two white LEDs (1W), one blue LED (1W) and one red LED (3W) provide the flux ratio in the blue/green/red regions of the total spectrum equal to 26/15/59 that is close to the target flux ratio equal to 30/20/50. The radiation spectrum of the irradiator with this flux ratio is shown in figure 1.

A more economical version is a two-color irradiator which consists of the white Nichia LED and red Philips LED. However, this combination cannot provide the Protasova's value. A special LED with an enhanced blue component in the radiation spectrum is required to implement this version. However, the spectrum of the three-color irradiator is easier to change if compared to that of the two-color one.

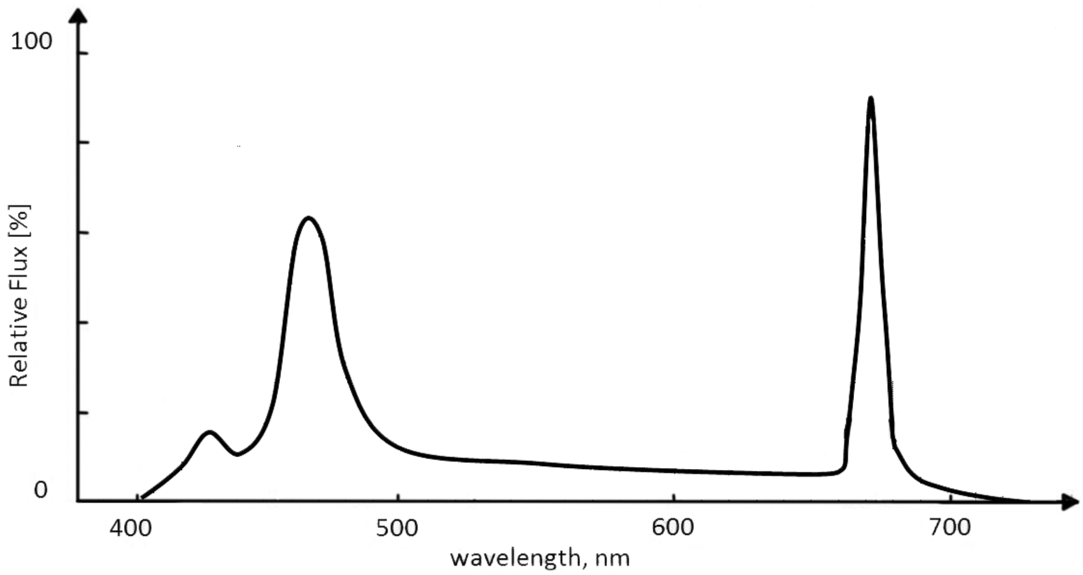

Figure 1. Irradiation spectrum of the combination of the warm white and blue Nichia LEDs and red Philips LED.

Another important task is to develop an optimal design of the emitter and optimal light intensity curve (LIC). The main purpose of the proposed irradiator is supplementary lighting of tall plants in industrial greenhouses. The irradiator should be of the sizes to provide the lowest shading coefficient. LED sources make possible to develop irradiators of virtually any shape and power. Since tall plants (cucumbers, tomatoes) in a greenhouse are planted in a long row one meter apart, it is advisable to make a fixture with a length of 1–1.5 meter with an approximate cross-section of $0.05x0.1m^2$ and to place it along the rows of plants. PHILIPS manufactures the irradiators of this size [1].

First of all, we find the location of the irradiator in the greenhouse and the predominant direction of the flux incident on tall plants. The analysis showed the optimal location of fixtures at a height of 4–6 meters (typical greenhouse) above the rows of plants. In this case, the side lighting of the plant can be arranged to provide sufficiently uniform irradiation of all the leaves along the stem. The selected scheme of lighting fixtures exposure and location is shown in figure 2 (a).

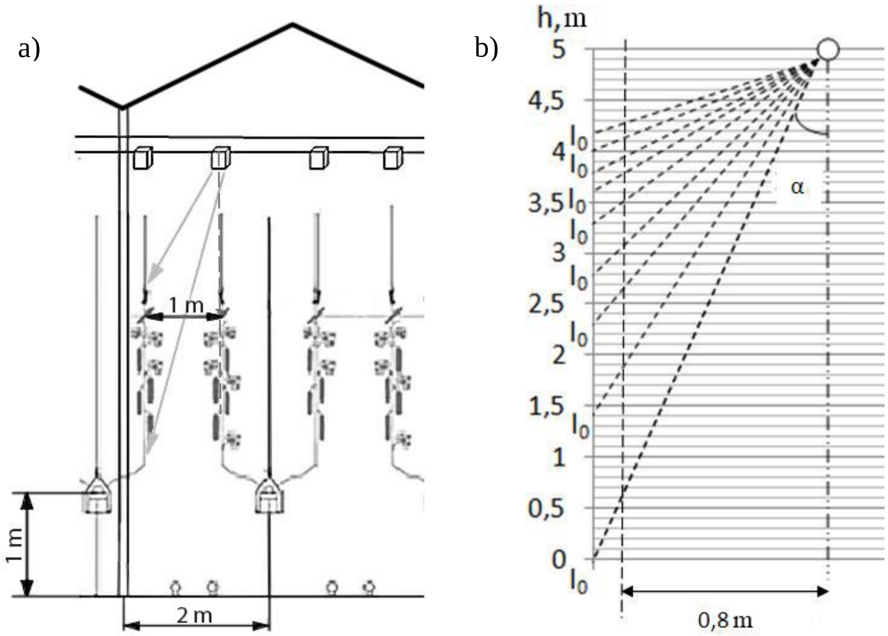

Figure 2. Arrangement of plants, fixtures, areas, and direction of incident beams (a), and the schematic diagram of the LIC model for LED irradiator (b).

To calculate IF, it is required to determine the model of the plant. For closely planted low-growing plants, IF can be modeled as a flat horizontal plate [12, 13]. Modeling of IF for tall plants several meters high is more complicated. In our opinion, a good approximation is a distribution of irradiance when it is uniform in the areas located perpendicular to the direction of propagation of the beams incident on the plant at different angles along its axis (figure 2a, b). This modeling is similar to the arrangement of the leaves of plants.

We have considered two versions of light intensity curve formation. The first version considers a point radiation source. These properties can be inherent in irradiators formed by groups of LEDs. In this case, the irradiance in the area perpendicular to the direction of propagation of the beam I0 (figure 2, b.) is proportional to l_2, where l is the distance from the source to the point of the beam incidence on the vertical plane along the plant. Using this law, we found the target values of the initial intensities I01 for beams emitted by the point source at different angles with I_0 constant at any point of the calculated vertical plane. To perform the calculation, we placed the vertical plane at a distance of 0.2 m from the plant stem, i.e. at a distance of 0.8 m from the light source.

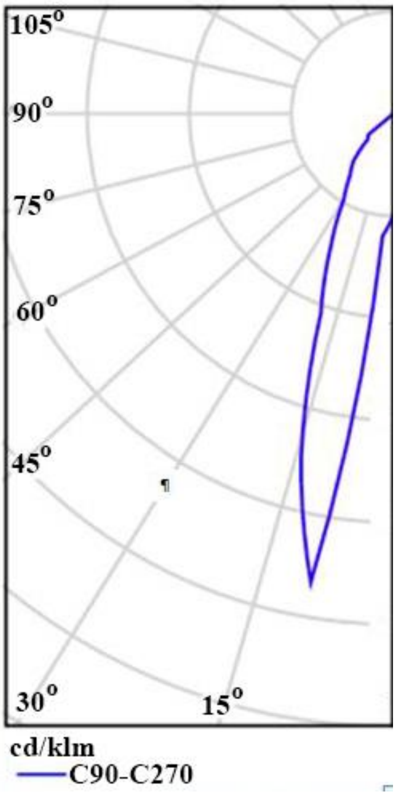

Figure 3. LIC of the irradiator in the IES format for point light source

The calculation data was used to plot LIC in the form of the dependence $I_{01}=f(\alpha)$, where α is the angle between the vertical plane and the direction of beams. To calculate and analyze the irradiance, the IES file (figure 3) was formed using the DIALux software.

After that, we simulated the radiance distribution for different planes of the model greenhouse facility with lamps of the calculated LIC. The analysis of the results suggests the following findings and conclusions.

3. Conclusions

An optimal version of the reference spectrum for adaptive irradiator is a three-color irradiator with white LED emitting in a broad spectral range (400–750 nm). Energy-efficient two-color irradiator can be designed based on red and white LEDs with increased blue component in the radiation spectrum. An optimal irradiator for tall plants should have a spot light distribution diagram. To calculate IF (irradiance standardization) for greenhouses with tall plants, it is necessary to develop a plant model taking into account the geometry of leave arrangement along the stem. Irradiators with the calculated LIC can uniformly irradiate both tall and low growing plants, so they can be used for growing all kinds of plants in greenhouses of various types.

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