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Optimizing the spectral composition of light from LED phytolighting systems to improve energy efficiency

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Abstract. The use of LEDs for plant lighting (phytolighting) provides a more energy-efficient alternative to traditional lighting methods. Combination of LEDs with different spectral composition and the possibility to change the composition of resulting radiation in a single lighting device allows one to improve the efficiency of phytolighting systems and optimize them for different conditions of plant growth and development. In this work, we have investigated quasi-monochromatic LEDs specialized for efficient phytolighting and efficient white LEDs with different CRI. Being based on the research, the most effective LEDs for building phytolighting systems have been identified, and their optimal ratio with red quasi-monochromatic LEDs for building phytolighting systems in rooms with a constant presence of people (greenhouses, winter gardens, *etc*) has been determined.

Keywords: LED, phytolighting, photosynthetic efficiency, indoor farming, artificial lighting, correlated color temperature, color rendering index.

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1. Introduction

Lighting of plant crops (phytolighting) is an important factor that significantly affects the growth and development of plants. LED-based phytolighting systems have revolutionized the field of indoor agriculture and crop cultivation in closed controlled environments due to the possibility of optimizing the spectral composition of phytolighting [1, 2]. Over the past decades, it has been proven that LED lighting systems can serve as an energy-efficient alternative to systems based on incandescent, fluorescent, and sodium lamps [3]. Implementation of LED-based lighting by using quasi-monochromatic radiation allows for activation of specific photomorphogenic, biochemical or physiological reactions of plants, and the use of LED radiation of a certain spectral composition (*e.g.* UV radiation) allows for the control of plant pests and diseases [4]. In addition, LED phytolighting significantly reduces electricity consumption for growing plants not only due to the high energy efficiency of LEDs, but also due to the possibility of optimizing the spectral composition of radiation, which ensures appropriate levels of biological impact at a lower overall intensity. The use of modern semiconductor structures and available materials, such as macroporous silicon [5–7], graphene [8, 9], carbon nanotubes [10], *etc*., to create semiconductors, further increases the power and reduces the cost of semiconductor components, which significantly expands their applications. Introduction of new materials [11] and methods of their diagnostics [12] for LED production accelerates the process of large-scale production of modern high-performance lighting systems.

One of the most important requirements for industrial phytolighting systems is their high power and uniform distribution of light flux [13]. Modern LEDs make it possible to create powerful lighting systems by using one [14] or several powerful LEDs or LED COB modules [15]. Increasing the power of individual LEDs to ensure the required level of biological light exposure requires application of new highly efficient cooling systems, in particular, based on heat pipes [16, 17] and thermosyphons [18, 19]. These powerful lighting devices can be used when placed at high altitudes as an alternative to classical phytolighting systems based on discharge lamps. The most effective in terms of luminous flux utilization is the placement of phytolighting systems at a short distance from the plants, which use low-power LEDs combined into LED clusters. The use of LEDs with different spectral compositions in these clusters allows implementation of lighting with the ability to adjust the spectral composition of the resulting light [20]. Such clusters can include both white broadband and coloured quasi-monochromatic LEDs and have the ability to control the emission power of individual LEDs or their specific groups.

In contrast to the human eye's perception of light radiation, which is related to the visibility curve of the human eye, the degree of biological effect of light on plants is subject to a different relationship – the photosynthetic efficiency curve [1]. That is why, when creating the energy-efficient phytolighting systems, it is necessary to take into account the efficiency of the LED spectrum for photosynthesis.

The aim of this work was to determine the energy efficiency of different type LEDs for plant lighting and to optimize the resulting lighting spectrum for energy-efficient phytolighting systems implemented using quasi-monochromatic and broadband white LEDs.

2. Methods for assessing the efficiency of phytolighting systems

Only a part of the electrical power (P_e) supplied to the LED is converted into light radiation, and the rest is converted into thermal power. If P_r is the luminous radiation power of LED, then the radiation efficiency (η) can be defined as:

$$\eta = \frac{P_r}{P_e}. \quad (1)$$

To take into account the effect of light of a given spectral composition on the course of photoinduced processes in plants, such a parameter as the photosynthetic photon flux density (PPFD) is used [3], which depends on the radiation power within the wavelength range of 400 to 700 nm. To determine PPFD, the following relationship can be used:

$$\mathrm{PPFD} = \frac{\mathrm{PPF}}{S}, \quad (2)$$

where PPF is the number of photosynthetically active photons (intensity of photosynthetically active radiation flux) per area S to which they are directed. PPF can be considered as the equivalent of the luminous flux of a lighting fixture in relation for human illumination, while the PPFD can be seen as the equivalent of illuminance.

The efficiency of the spectrum for phytolighting can be assessed using the parameter of its photon efficiency (PE), which is calculated as:

$$\mathrm{PE} = \frac{\mathrm{PPF}}{P_r}. \quad (3)$$

It is more expedient to use the parameter of photosynthetic radiation efficiency, *i.e.*, the number of photons active for photosynthesis per unit of electrical energy consumed by the lighting system, which is also called photosynthetic photon efficiency (PPE), to determine the energy efficiency of phytolighting systems. Photosynthetic photon efficiency can be calculated as:

$$\mathrm{PPE} = \mathrm{PE} \cdot \eta. \quad (4)$$

When calculating PPF, the use of photons from the wavelength range 400 to 700 nm by plants is considered to be the same, which is not entirely accurate when assessing the efficiency of phytolighting in more detail. To take into account the efficiency of radiation with different wavelengths for photosynthesis, such a value as the "photon flux absorbed by the plant" – Yield Photon Flux (YPF) can be used. YPF is measured similarly to PPF in micromoles per second, but is calculated taking into account the weighting factor for different photosynthetic photons of each wavelength in the spectral range 360…760 nm in accordance with the radiation efficiency curve (Fig. 1) for the photosynthetic process (relative quantum efficiency, RQE). Taking into account RQE allows taking into account the efficiency of radiation at different wavelengths for the photosynthetic process [1].

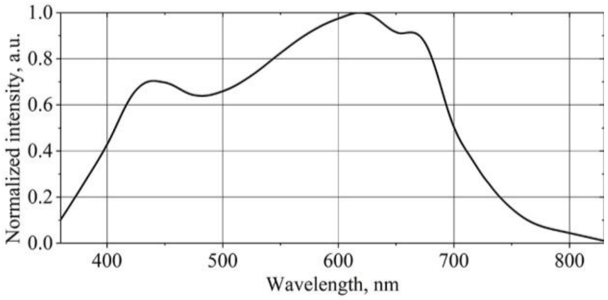


Fig. 1. Radiation efficiency curve for photosynthesis.

PPF is always slightly higher than YPF (the value of the photosynthesis RQE curve is less than unity in most of the spectrum), so it is beneficial for manufacturers of phytolighting systems to use PPF, often without taking into account η, to demonstrate the advantages of their products.

In this paper, it is proposed to use the ratio of YPF to P_r (YPF/P_r) and the ratio of YPF to P_e (YPF/P_e), which are the most reliable indicators of the efficiency of phytolighting systems, in addition to PPE, to assess the efficiency of using the spectral composition of radiation of different types.

3. LEDs for implementation of energy-efficient phytolighting systems

The energy efficiency of LED phytolighting systems mainly depends on the type of LEDs they are based on. The ability to create specific emission spectra with LEDs allows for the creation of energy-efficient light-emitting structures specialized for application in phytolighting systems. To determine the types of LEDs that can be effectively used for lighting plant crops, it is necessary to determine the electro-optical parameters of LEDs, which will allow one to assess the energy efficiency of their use in phytolighting systems.

To determine the electro-optical parameters of LEDs, we used a complex based on a CAS 140 spectrometer, a 2 m diameter integrating sphere, and a HAMEG HMP4040 DC power supply. The supply voltage and current as well as the radiation power (P_r) were measured. The electrical power (P_e) was calculated.

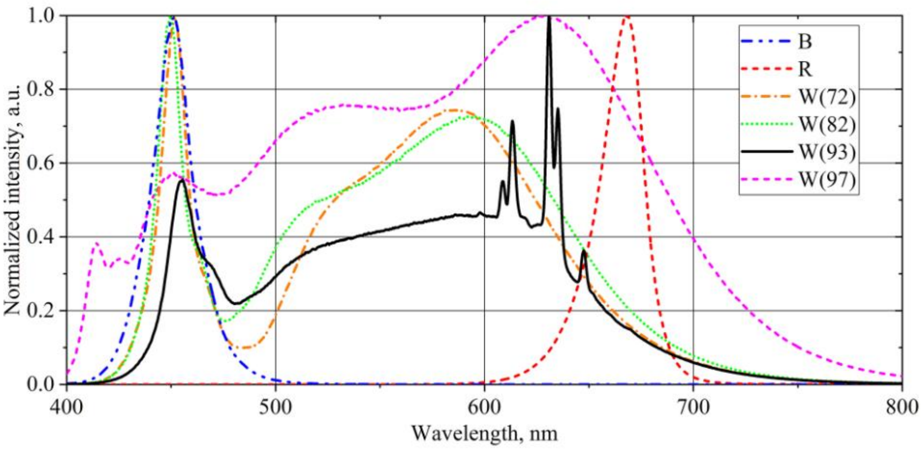


Fig. 2. Normalized spectra of quasi-monochromatic and white LEDs.

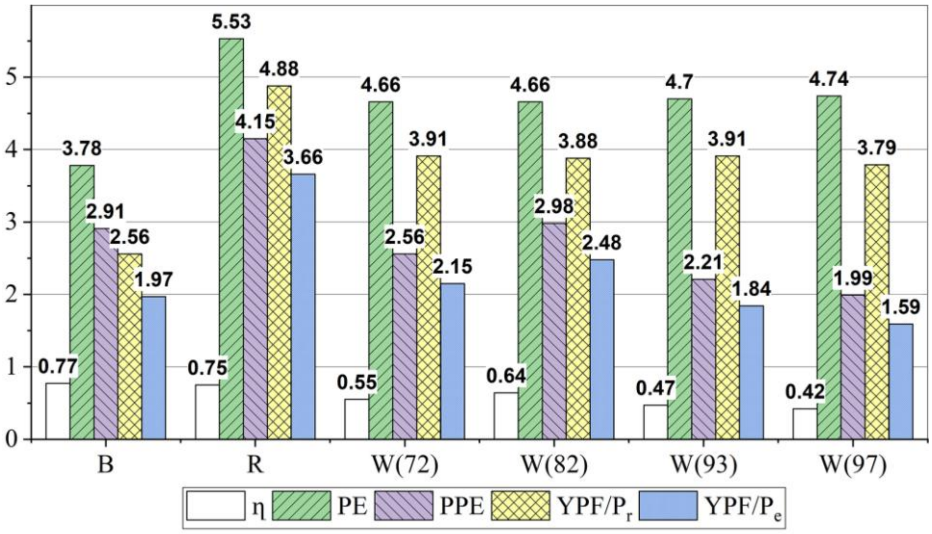


Fig. 3. Parameters of LEDs for phytolighting systems.

The determined radiation spectrum allowed the software developed in [20] to be modified to calculate PPF and YPF. Using the dependences (1)–(4), the values of η, PE, PPE, and YPF/P_e were obtained.

Specialized quasi-monochromatic LEDs for plant lighting [21] with peak wavelengths in the most efficient spectral regions for photosynthesis were selected as the LEDs under study and manufactured using optimized technological processes. White LEDs [18] with a correlated colour temperature (CCT) of about 4000 K, which had the highest energy efficiency among the analogues ones, as well as white LEDs with a wide spectrum [22–24], were studied. The colour rendering index (CRI) of the selected white LEDs ranged from 72 to 97 units. In what follows, the selected LEDs will be denoted as: B – blue, R – red, and the names of the white LEDs are represented as W(*x*), where *x* is CRI of the corresponding white LED. Fig. 2 shows the spectra of blue and red quasi-monochromatic LEDs, as well as the spectra of white LEDs with CRI 72…97. Higher CRI LEDs have a higher emission power in the red part of the spectrum, so they are generally considered to be more efficient for phytolighting.

Fig. 3 shows the determined η, PPE, and YPF/P_e of quasi-monochromatic and white broadband LEDs that can be used to implement phytolighting systems. The parameters were determined at the nominal LED supply current and a housing temperature of about 25 °C.

The results of the study indicate the highest energy efficiency of red LEDs, which peak wavelength is close to the corresponding maximum of the RQE curve of photosynthesis. White LEDs have similar PEs (from 4.66 to 4.74 µmol/J), but their radiation efficiency differs significantly (from 0.42 to 0.64). Among white LEDs, there is a slight increase in PE of LEDs with an increase in their CRI. However, with increasing CRI, the radiation efficiency decreases, which leads to a decrease in PPE for LEDs with CRI above 90.

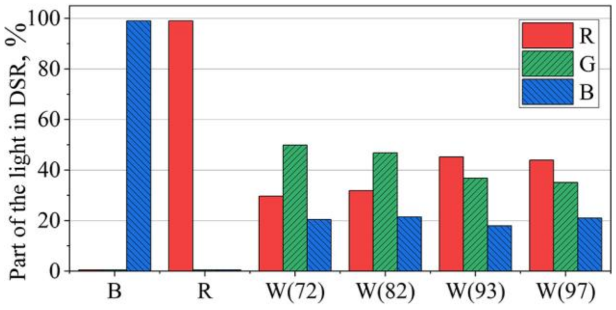


Fig. 4. Part of the light in different spectral ranges (DSR) for the studied LEDs.

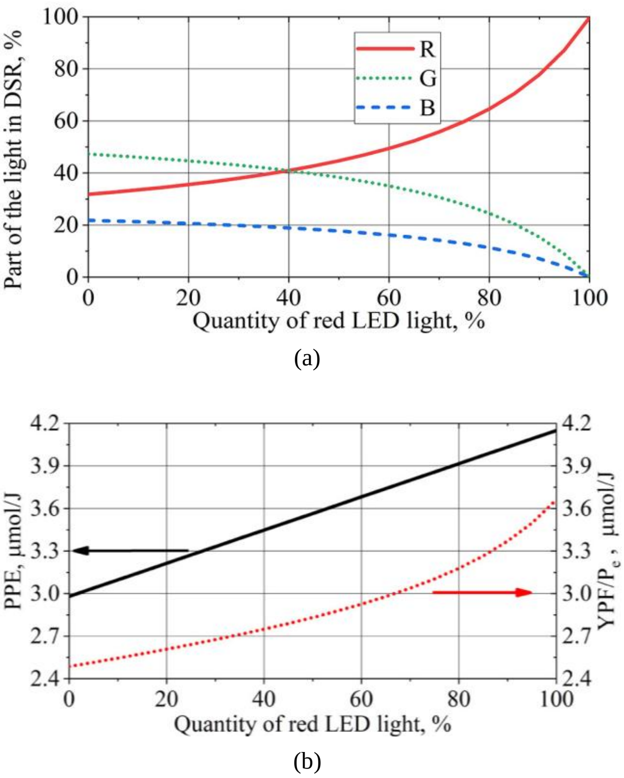
4. Optimization of the spectrum of energy-efficient phytolighting

The results of the performed research indicate that the most energy-efficient phytolighting systems will be based on red and blue LEDs. However, white W(82.4) LEDs have PPE and YPF/P_e higher than blue quasi-monochromatic LEDs. At the same time, their η is only 13% lower than that of blue LEDs.

The studies [25, 26] show that, in general, PPF requires 5% to 20% of radiation in the blue region of the spectrum to improve plant development and minimize their shade avoidance reaction. When illuminated only with quasi-monochromatic blue and red LEDs in the recommended ratio [3] of their luminous fluxes of 1:4, PPE of the resulting radiation will be 3.90 μmol/J, and the YPF/P_e of this system will be 3.32 μmol/J. The disadvantage of such quasi-monochromatic lighting is a significant colour distortion and low CRI, which negatively affects the psychophysical state of people who are or work in the maintenance of crops with this type of lighting.

A significant number of studies indicate the importance of the presence of radiation in the green spectrum in the spectrum of phytolighting [27–29]. One of the most effective ways to provide radiation in the green region of the spectrum is to add broadband white LEDs to quasi-monocromatic LEDs. In addition, white LEDs have a significant portion of radiation in the blue region of the spectrum. At the same time, the overall spectrum of white LEDs almost corresponds to RQE. If we consider the spectral ranges of emission in the blue region of the spectrum to be in the range of 400 to 500 nm, in the green 500…600 nm, and in the red 600…700 nm, then for the studied LEDs we can build diagrams of the intensity distribution in each of the spectral regions (Fig. 4).

Fig. 4 shows that the radiation power in the green spectral region for all white LEDs is more than 35%, and in the blue spectral region it is 18…22%. At the same time, the most efficient white LEDs W(82) have only 32% of their emission in the red spectral region This type of LED is used as an independent solution for building phytolighting systems based on white LEDs only [30]. One of the ways to further improve the efficiency of a phytolighting system based on these white LEDs is to add some additional red LEDs. The modelling of the parameters of the resulting phytolighting radiation for different ratios of red quasi-monochromatic and selected efficient white LEDs W(82) is shown in Fig. 5.



(a)

(b)

Fig. 5. Dependence of the normalized radiation power in different spectral ranges (a) and the phytolighting parameters (b) on the contribution of the red LED added to the resulting light radiation.

As can be seen from Fig. 5, when the red component is added to the radiation of the LED, the amount of radiation in other areas of the spectrum decreases and remains at a sufficiently high level, while the PPE and YPF/P_e parameters increase. Taking into account that people may be present in the rooms where the phytolighting is implemented, we calculate the CCT and CRI parameters of the lighting system built on the basis of these LEDs for the resulting radiation. Fig. 6 shows the dependence of CCT and CRI on the contribution of the red LED to the resulting light emission. The criterion of sufficiency for human perception of this light as white was assumed to be that the chromaticity coordinates of the synthesized radiation should be no more than 0.006 away from the Planck curve in the CIE1931 chromaticity diagram.

Fig. 6 shows that adding 22% of the red LED power to the white LED leads to a decrease in the CCT by only 503 K and an increase in the CRI to 93 units, which has a positive effect on the human perception of objects illuminated by such light. PPE and YPF/P_e of the lighting system with the addition of 22% of the red LED radiation power to the selected white LED W(82), are measured to be 3.18 and 2.65 μmol/J, respectively.

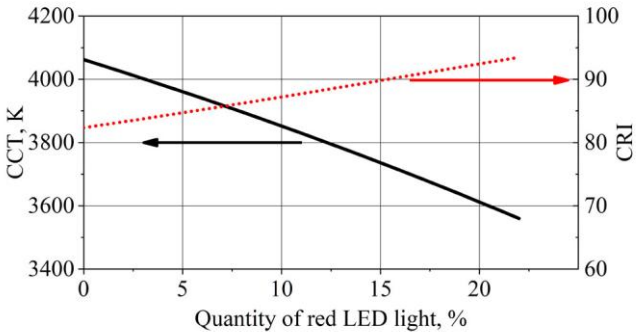


Fig. 6. Dependence of CCT and CRI on the contribution to the resulting light output of the red LED.

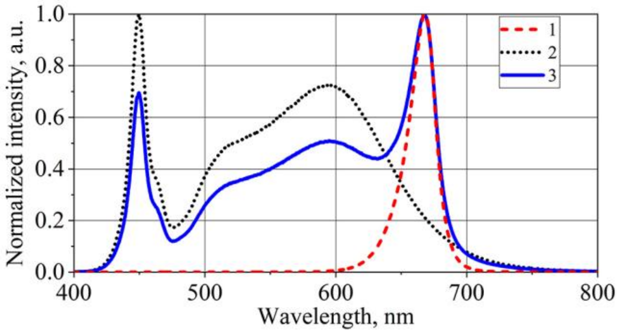


Fig. 7. Normalized spectra of red quasi-monochromatic (*1*), white (*2*) LEDs and the resulting spectrum (*3*).

Fig. 7 shows the normalized spectrum of the white LED W(82) – curve *1*, the spectrum of the red LED – curve *2* and spectrum synthesized by adding a part (22%) of the red LED radiation power to W(82) – curve *3*.

These lighting systems can be used not only in specialized agricultural facilities, but also in premises with a permanent presence of people, where plant cultivation is provided (greenhouses, winter gardens, *etc*).

5. Conclusions

Being based on the recommendations for the spectral composition of radiation intended lighting of plant crops, the requirements for the spectral composition of light of phytolighting systems were determined.

The efficiency of LEDs with different spectral compositions and the most energy-efficient LEDs for use in phytolighting systems have been experimentally determined. The studied LEDs have photon efficiencies ranging from 3.78 μmol/J (quasi-monochromatic blue LEDs) to 5.53 μmol/J (quasi-monochromatic red LEDs). White LEDs, depending on CRI, have photon spectral efficiencies ranging from 4.66 to 4.79 μmol/J. The highest radiation efficiency of quasi-monochromatic LEDs led to their significant advantage in implementation of phytolighting systems.

Some modern white LEDs with high CRI and photon efficiency allow us to create phytolighting systems based on them that are close to phytolighting based on quasi-monochromatic LEDs. PPE of these white LEDs, and even more, so the radiation efficiency, taking into account the RQE curve of photosynthesis, can be significantly lower.

Phytolighting systems based on white LEDs with red LEDs radiation can have comfortable for humans CPI and PPE indicators, when providing phytolighting parameters at the level of systems based on quasi-monochromatic LEDs. These systems can be used not only at specialized agro-industrial facilities but also in premises with a permanent presence of people where plant cultivation is provided (greenhouses, winter gardens, *etc*).

Further investigation could focus on optimizing the spectrum composition of radiation emitted by specialized light-emitting structures to enhance the energy efficiency of phytolighting use.

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Minyaylo M.A.: validation, investigation, writing – review & editing.

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Оптимізація спектрального складу світла світлодіодних систем фітоосвітлення для підвищення енергоефективності

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Анотація. Використання світлодіодів для освітлення рослин (фітоосвітлення) є більш енергоефективною альтернативою традиційним методам освітлення. Поєднання світлодіодів з різним спектральним складом та можливість змінювати склад результуючого випромінювання в одному освітлювальному приладі дозволяє підвищити ефективність систем фітоосвітлення та оптимізувати їх для різних умов росту і розвитку рослин. У цій роботі ми досліджували квазімонохроматичні світлодіоди, спеціалізовані для ефективного фітоосвітлення, та ефективні білі світлодіоди з різним CRI. На основі проведених досліджень визначено найбільш ефективні світлодіоди для побудови систем фітоосвітлення, а також їх оптимальне співвідношення з червоними квазімонохроматичними світлодіодами для побудови систем фітоосвітлення у приміщеннях з постійною присутністю людей (теплицях, зимових садах тощо).

Ключові слова: фітоосвітлення, світлодіод, ефективність фотосинтезу, землеробство закритого ґрунту, штучне освітлення, корельована колірна температура, індекс кольоропередачі.