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High-power light-emitting diode based facility for plant cultivation

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Abstract

Based on perspectives of the development of semiconductor materials systems for high-power light-emitting diodes (LEDs), an illumination facility for greenhouse plant cultivation was designed with the dominating 640 nm photosynthetically active component delivered by AlGaInP LEDs and supplementary components from AlGaN (photothropic action, 455 nm) and AlGaAs (photosynthetic 660 nm and photomorphogenetic 735 nm) LEDs. Photosynthesis intensity, photosynthetic productivity and growth morphology as well as chlorophyll and phytohormone concentrations were investigated in radish and lettuce grown in phytotron chambers under the LED-based illuminators and under high-pressure sodium (HPS) lamps with an equivalent photon flux density. Advantages of the high-power LED-based illuminators over conventional HPS lamps, applicability of AlGaInP LEDs for photosynthesis and control of plant growth by circadian manipulation of a relatively weak far-red component were demonstrated.

1. Introduction

Artificial lighting for plant cultivation is an important factor, which determines the cost and nutritional quality of greenhouse vegetables. Efficiency of greenhouse lighting has been improved by application of high-pressure sodium (HPS) lamps, which emit predominantly yellow–red light effectively absorbed by chlorophylls. The improvement is achieved owing to a high overall light yield and the emission spectrum suitable for plant cultivation. However, application of light sources with a spectrum substantially different from the solar one, encounters difficulties owing to sensitivity of plants to the spectral composition of light. Particularly in HPS lamps designed for horticulture applications, the blue component can be enhanced; however, a further purposeful tailoring of the spectrum in the red region has physical limitations. In principle, the spectrum can be adjusted using phosphors, but data on the spectrum optimal for particular plants are still scarce and fragmental.

Light-emitting diodes (LEDs) present a versatile alternative for artificial greenhouse lighting with numerous advantages. In comparison with conventional HPS and fluorescent lamps, LEDs are an energy-efficient, environment-friendly and longevous source of light. Assembling of LEDs, which are already available in the entire relevant spectral range from near infrared (IR) to near ultraviolet (UV), enables one to tailor the spectrum for optimal growth. Contrary to discharge lamps, efficiency of LEDs has no physical limitations up to 100% (the values above 50% have been already demonstrated [1]). Finally, solid-state lighting technology offers completely new possibilities in plant cultivation, such as use of pulsed illumination and dynamic adaptation of the spectrum within circadian cycle and at different phases of growth.

However, because of high cost of LEDs in comparison with conventional lamps, only specifically targeted applications, such as space-based plant growth facilities [2, 3] and hydroponic laboratory photobioreactors for high-density plant cultivation [4], exhibited viability at the early stage of this revolutionary technology. These first facilities contained a huge amount of low-power and relatively inefficient LEDs (several units per square centimetre), which also made the price of assembling high. However, the increase in the optical output per chip by a factor of 20 per decade (Haitz's Law) [5] and the drop in price per unit of flux generated by approximately a factor of 10 per decade, give rise to optimism that mass application of LEDs in phytotrons and greenhouses is feasible in the coming decades.

Here we consider the present status and future trends of LED technology relevant to plant cultivation and report on a four-wavelength illuminator designed based on these considerations. We demonstrate growth experiments for lettuce and radish using light of different spectral composition and compare biometric parameters and concentrations of chlorophyll and phytohormones in plants grown under illumination by high-power LEDs and HPS lamps with a similar photon flux.

2. Selection of LEDs for plant cultivation

Plants' basic need for light reside within three spectral ranges responsible for photosynthesis, phototropism and photomorphogenesis, respectively. Photosynthesis requires light in the vicinity of the absorption peaks of chlorophylls *a* and *b* (at 662 nm and 642 nm, respectively), which are the most important photosynthetic pigments. Phototropic processes, which control motion of plant organs in response to light and ensure optimization of biophysical and biochemical reactions, are triggered by light with wavelengths in the range of 400–500 nm. Finally, plant morphogenesis, encompassing processes such as shooting, pigment synthesis and healthy plant development, depends on far-red radiation in the range of ~730–735 nm. Accordingly, in the active layers of the LEDs, appropriate semiconductor materials systems with the compositionally tailored band gap should be exploited. Efficient generation of light with the required wavelengths relies basically on three group III–V materials systems, namely, AlGaAs, AlGaInP and AlInGaN [6].

Direct-gap $Al_xGa_{1-x}As$ system is favourable for semiconductor heterostructures used in LEDs owing to lattice match of the alloys of different compositions. The structures are fabricated by relatively inexpensive liquid-phase epitaxy (LPE) and cover the range of wavelengths from 870 nm ($x = 0$) to 624 nm ($x = 0.45$). The alloy with the Al molar fraction x of about 0.2 is the most suitable material for the active layer of double-heterostructure 730 nm LEDs, which are commercially available with radiant efficiencies of about 20%. However on decreasing the wavelength below 700 nm, the efficiency of radiative recombination in AlGaAs decreases because of the proximity of the direct-to-indirect band crossover. Since the sensitivity of human vision in the red region increases with decreasing wavelength, the luminous efficiency has a peak at about 660 nm [7]. This justifies mass production of 660 nm LEDs primarily for visual (signal) applications. Owing to the match with the absorption peak of chlorophyll *a*, these LEDs were first adopted for plant cultivation in 1991 [2]. However, radiant efficiency of 660 nm AlGaAs LEDs is limited to about 21% and is below 15% in commercial devices [8]. Also, AlGaAs alloy with a high content of Al, suffers from enhanced deterioration of the material. Although comparatively inexpensive, LPE technology is unable to ensure sufficient oxygen decontamination, while aluminium, tends to form oxygen-rich compounds through hydrolysis [9]. Such degradation is enhanced during high-temperature, high-humidity operation [10] and imposes restrictions on the thermal regime of the LEDs and greenhouse applications, respectively. In combination with the temperature-invoked occupation of the indirect band, this makes devising of high-power, single-chip AlGaAs LEDs for the 660 nm wavelength impracticable.

An alternative to photosynthetically important wavelengths is offered by the AlGaInP materials system. Direct-gap $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ alloy, which is lattice matched to GaP independently of the Al molar fraction x, is a suitable material for the active layers of LEDs emitting in the range of 652 nm ($x = 0$) to about 580 nm ($x = 0.4$). Although the efficiency of radiative recombination in this material also suffers from the presence of an indirect band, this effect is much smaller and less temperature sensitive in low Al content AlGaInP alloy than in AlGaAs emitting at 660 nm. The AlGaInP structures are fabricated using metalorganic chemical vapour deposition (MOCVD), which is a more advanced technique for diminishing materials contamination in comparison with LPE used for AlGaAs growth. These advantages of the AlGaInP system enable operation of the LEDs in high-power regime, thus substantially reducing the price of both devices and assembling. Single-chip 652 nm (GaInP) truncated-inverted-pyramid LEDs of 1 W electrical power have already been demonstrated and have exhibited record external quantum efficiency in excess of 50% [1]. At present, high-power LEDs with peak wavelengths of about 640 nm are being produced on a large scale, mainly for visual (signal) applications, since they have the highest luminous efficiency in the red region. Meanwhile, shifting of the peak wavelength to 652 nm is technologically simple. Moreover, it is favourable because of a higher radiant efficiency and reduced temperature sensitivity of the resulting LEDs. However, a possible drawback of the AlGaInP LEDs for photosynthetic applications is that the major part of the emission is absorbed by chlorophyll *b*, which can disturb the natural ratio of chlorophylls in plants.

Finally, the most advanced and cost-efficient component of plants' illumination relies on the blue emission provided by AlInGaN LEDs, which was introduced for plant cultivation [11] soon after their invention in 1994 [12]. Nitride LED structures are deposited over lattice mismatched sapphire using MOCVD and already exhibited radiant efficiencies in excess of 40% [13]. They do not suffer from occupation of the indirect band and exhibit low temperature sensitivity. This makes the AlInGaN materials system attractive for application in high-power LEDs. Such LEDs with the electric power of up to 5 W have already been put on the market [14]. Actually, the wavelengths generated in AlInGaN potentially span from 200 nm (AlN) to about 1.5 μm (InN); however, because of materials quality issues, commercially available high-power nitride LEDs emit in the spectral region ranging only from near UV to green. Blue nitride LEDs have potential for further increase in power and reduction in price, since they provide a base for white-LED technology, which is being heavily promoted for general lighting applications [6].

3. High-power solid-state lighting facility

Based on the above considerations, the lighting facility was designed using the most advanced LEDs. The facility featured modular design for parallel growth runs under different lighting conditions. Each module has an illuminated area of 0.22 m^2, sufficient for simultaneous growth of vegetable plants such as lettuce and radish required in large amounts for acquisition of statistically reliable data. In a departure from the conventional three-wavelength approach [15], four groups of LEDs with different peak wavelengths were used in the facility. The main photosynthetically active photon flux within the module was provided by 100 units of 1 W AlGaInP single-chip LEDs with the peak wavelength of 640 nm and about 120 mW optical power each (Luxeon^{TM} type LXHL-MD1D of Lumileds Lighting, USA). To control the ratio of photosynthetic flux for chlorophylls *a* and *b*, the AlGaInP LEDs were supplemented by 9 units of AlGaAs multichip illuminators, each containing 60 AlGaAs 660 nm chips mounted on a metal stem with AlN ceramics for improved heat management (L660-66-60 of Epitex, Japan; 2.4 W electrical and 180 mW optical power each). The blue component of the spectrum was built up using 4 units of 5 W blue LEDs emitting at 455 nm peak wavelength with 0.5 W optical power each (Luxeon^{TM} type LXHL-LR5C of Lumileds Lighting, USA). The facility was accomplished by 22 units of 90 mW far-red LEDs delivering 18 mW optical power at 735 nm peak wavelength each (L735-05-AU of Epitex, Japan). The LEDs were mounted on an aluminium reflector also serving as a heat sink and were uniformly arranged to ensure optimal homogeneity of the flux. The normalized emission spectra of the LEDs used are presented in figure 1(*a*).

The far-red 735 nm AlGaAs LEDs featured the highest radiant efficiency (20%), whereas the blue AlInGaN LEDs were the most efficient in terms of the device price per unit flux emitted. The red AlGaAs LEDs had the lowest ranks in both the radiant efficiency (7.5%) and device price, i.e. in the overall cost of lighting.

The flux for each spectral component was controlled by independent variation of the driving current for each of the four groups of LEDs using high-power current regulators. The photon flux densities at the nominal driving currents were 9 μmol m^{-2} s^{-1}, 150 μmol m^{-2} s^{-1}, 9.5 μmol m^{-2} s^{-1} and 3 μmol m^{-2} s^{-1} for the 455 nm, 640 nm, 660 nm and 735 nm components, respectively. Figure 1(*c*) shows the flux density for each component as a function of driving current.

During the first year of operation the high-power LEDs exhibited some deterioration, mainly owing to the darkening of the plastic encapsulant. This effect was higher in LEDs emitting at shorter wavelengths.

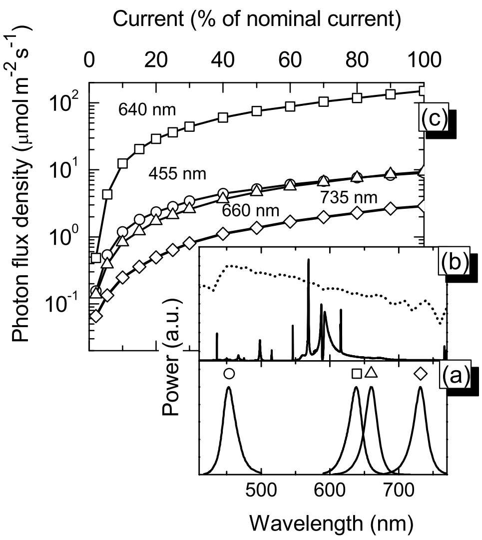

Figure 1. (*a*) Normalized emission spectra of the LEDs used in the illuminator; (*b*) spectra of HPS lamp (——) and Commision Internationale de l'Éclairage (CIE) daylight standard illuminant D_{65} (· · · · · ·); (*c*) photon flux density provided by four LED groups as a function of driving current.

4. Growth treatments

The high-power LED-based facility was tested in plant growth experiments with different illumination regimes. Lettuce (*Grand Rapids*) and radish (*Saxa*) were grown under otherwise identical conditions in phytotron chambers using peat substrate. The temperature in the phytotron was maintained at 21°C in the daytime and 17°C at night. To reveal statistically significant changes, 60 seedlings were planted at the beginning of each experiment. Ten seedlings (evenly picked from the entire area) were removed every week for measurements.

Below we specify four different treatments that are schematically presented in figure 2. The first treatment (EXP1), with the photon flux density of 9 μmol m^{-2} s^{-1}, 120 μmol m^{-2} s^{-1}, 9.4 μmol m^{-2} s^{-1} and 2.9 μmol m^{-2} s^{-1} for the spectral components of 455 nm, 640 nm, 660 nm and 735 nm, respectively, was used in the reference growth run. In the second run (EXP2), the intensity of the main red component (640 nm) was decreased by a factor of 1.5 in order to reveal the sensitivity of the photosynthetic system to light almost resonant with the absorption spectrum of chlorophyll *b*, which might be important for the prospective complete substitution of red AlGaAs LEDs with more advanced AlGaInP ones. Both treatments were performed under a 14/10 h daytime/night cycle starting from 6 AM.

The other two treatments were targeted at the control of physiological processes in plants grown under high densities of red photosynthetic and blue phototropic fluxes by a relatively low far-red photomorphogenetic flux, which constituted only about 2% of the total flux. In treatment EXP3, the 735 nm

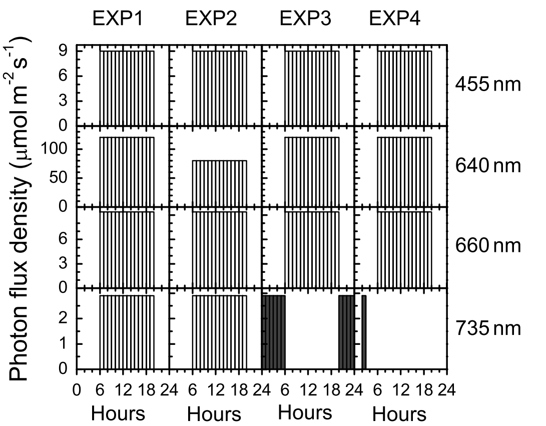

Figure 2. Circadian distribution of the photon flux density for the four spectral components (peaked at 455, 640, 660 and 735 nm), which were used in four growth treatments (EXP1 to EXP4).

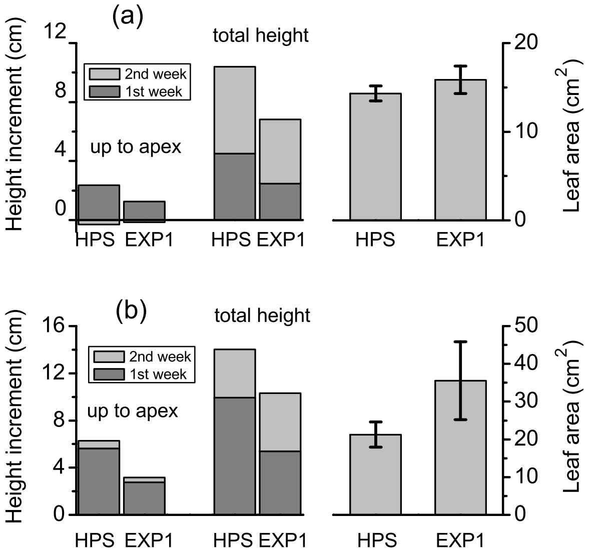

Figure 3. Biometric parameters of lettuce (*a*) and radish (*b*) grown under HPS lamps and under LED-based illuminator in treatment EXP1. Left, the increments of height until apex and of the total height measured at the stage of cotyledons formation (first week, dark grey columns) and after the leaves were formed (second week, light grey columns); right, leaf area two weeks after sowing.

far-red illumination was shifted from daytime to night. Since this treatment produced dramatic results (see section 5), an additional treatment (EXP4) with the far-red exposition reduced to 1 h in the middle of the nocturnal period (between 1 AM and 2 AM) was carried out.

Characteristics of plants grown under LED-based illumination were compared with those obtained under illumination by HPS lamps. SON-T-AGRO (Philips) lamps, which are designed for horticulture needs and have extra blue emission, were used (see spectrum in figure 1(*b*)). The photosynthetic photon flux density provided by the lamps in the spectral range of 400–700 nm was controlled using a photosynthesis system CI-310 (CID, Inc., USA) and maintained at the same level as in treatment EXP1.

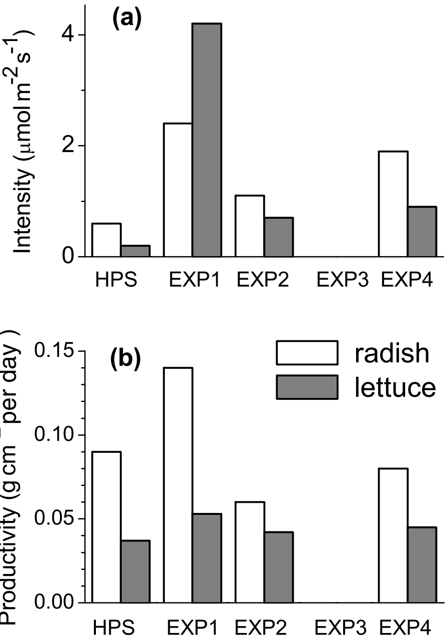

Figure 4. Net photosynthesis intensity (*a*) and photosynthetic productivity (*b*) of radish (white columns) and lettuce (dark columns) grown for two weeks under illumination by HPS lamps and under LED-based illuminator in treatments EXP1 to EXP4.

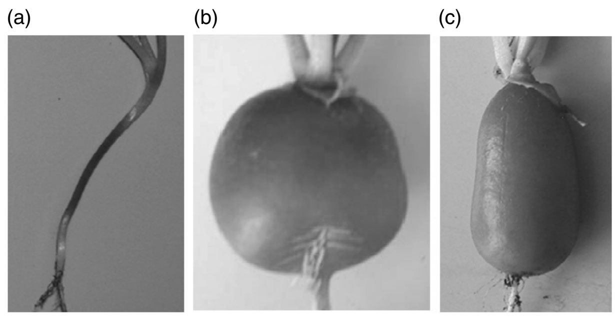

Figure 5. Typical rhizocarp shapes of radish grown under illumination by HPS lamps (*a*) and in treatments EXP1 (*b*) and EXP4 (*c*).

5. Results and discussion

Plants grown under different treatments were subjected to biometric measurements, measurements of the photosynthesis intensity (the rate of CO_2 assimilation per unit leaf area) using the photosynthesis system (CI-310), and determination of concentrations of chlorophylls (spectrometrically) and phytohormones (chromatographically). The increments in height (up to apex and total) were measured one and two weeks after sowing and the leaf area was determined after two weeks, as soon as the leaves were formed (figure 3). Two weeks after sowing, the photosynthesis intensity and the photosynthetic productivity (the mass of dry material produced via photosynthesis per unit leaf area per day) were determined (figures 4(*a*) and (*b*), respectively), the radish rhizocarp shape was examined (figure 5) and the concentration of chlorophylls (not shown) and phytohormones, gibberelic, abscisic and indole-3-acetic acids (GA_3, ABA and IAA, respectively) and zeatin, were measured (figure 6). The variation coefficient did not exceed 10% and 30% for the biometric measurements of height and leaf area, respectively, 15% for photosynthesis intensity and photosynthetic productivity and 5% for spectrometric and chromatographic measurements.

Although not completely optimized, the reference treatment under high-power LED illumination (EXP1) yielded more healthy growth of both cultivated species in comparison with the treatment under the HPS lamps. This is proved by compactness (smaller average height) of both radish and lettuce plants and a higher leaf area, especially for radish (figure 3). The most important improvement achieved was a dramatic increase in photosynthesis intensity by factors of 4 and 20 for radish and lettuce, respectively (figure 4(*a*)). Correspondingly, the photosynthetic productivity increased by factors 1.6 and 1.4, respectively (figure 4(*b*)). This resulted in the radish forming a full-size rhizocarp in two weeks under LED illumination (figure 5(*b*)), while under the HPS lamps, only a rudiment was set (figure 5(*a*)). Surprisingly, the observed improvements in photosynthesis and morphogenesis had a poor link to concentration of

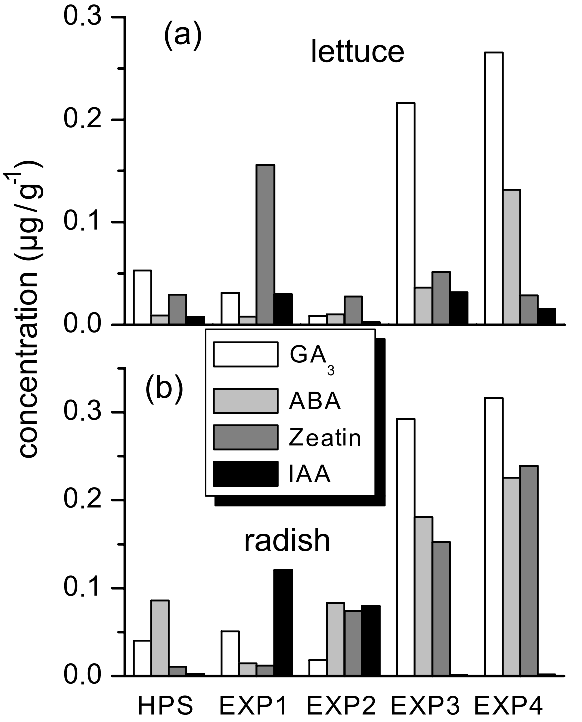

Figure 6. Concentration of phytohormones in lettuce (*a*) and radish (*b*) after two weeks of growing under different illumination spectra in treatments EXP1 to EXP4. Different column shading corresponds to gibberelic acid (GB_3), abscisic acid (ABA), zeatin and indole-3-acetic acid (IAA).

chlorophylls. The chlorophyll concentration in lettuce was about 9 $\mu g\, g^{-1}$ irrespective of the light source applied and exhibited some insignificant variation in radish. However, the crossover from HPS to LED illumination invoked noticeable changes in phytohormone concentration. In lettuce (figure 6(*a*)) the concentration of zeatin and IAA increased multifold. In radish (figure 6(*b*)) the most prominent was the increase in IAA and decrease in ABA concentration. In both species the concentration of GA_3 was the most insensitive to the illumination spectrum. Although phytohormones act in a complex and not completely unveiled way, we speculate that the observed changes in their concentration are coherent with the improvement in morphogenesis and productivity of the plants.

The results of the experiment with the reduced flux of the main 640 nm component delivered by the advanced AlGaInP LEDs (EXP2) demonstrated that this wavelength is primarily critical for photosynthesis. The reduction resulted in no significant variation of the biometrical parameters of both lettuce and radish, but there was clearly a drop in photosynthetic intensity and productivity (figure 4). The decrease in photosynthesis intensity and productivity was accompanied by a significant variation of the phytohormone concentration shown in (figure 6).

Circadian manipulations with the far-red component have demonstrated that the effect of high levels of red and blue light strongly depends on relatively low levels of morphogenetically active light. The shift of the 735 nm component from daytime to night (EXP3) resulted in almost complete inhibition of plant development through breakdown of the daytime photosynthetic process (figure 4). When the nocturnal far-red exposition was reduced to only 1 h (EXP4), the photosynthetic intensity and productivity recovered partially, exhibiting values somewhat smaller than those obtained for the reference treatment (EXP1) for radish and lettuce. Interestingly, application of a small amount of nocturnal far-red lighting resulted in remarkable morphological changes in radish, as evidenced by the formation of a typical cylindrical rhizocarp shown in figure 5(*c*). Also, low levels of nocturnal far-red light invoked significant changes in phytohormone concentration (figure 6).

6. Summary

In conclusion, a four-wavelength, solid-state lighting facility with the main photosynthetic component delivered by advanced high-power AlGaInP LEDs was demonstrated as a flexible tool for the study of plant growth. Growth of lettuce and radish under illumination with the dominating wavelength of 640 nm supplemented by 455, 660 and 735 nm components were shown to surpass that under the HPS lamp in photosynthesis and plant morphology characteristics. Meanwhile, circadian shifts of the relatively weak far-red 735 nm component were found to strongly influence the photophysiological processes in plants up to a complete breakdown of photosynthesis.

Application of advanced high-power AlGaInP and AlInGaN LEDs in plant cultivation facilities offers a substantial reduction in the relevant cost of light in comparison with conventional counterparts. However, further optimization of the spectrum and temporal profile of illumination for increasing productivity and nutritional quality of plants is required to make this technology attractive at least for phytotron applications. Finally, implementation of LED-based illumination for greenhouse plant cultivation relies on improving the performance and lowering the prices of high-power LEDs.

Acknowledgments

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