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Possible reasons of a decline in growth of Chinese cabbage under a combined narrowband red and blue light in comparison with illumination by high-pressure sodium lamp

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ABSTRACT

We attempted to elucidate possible reasons of a decline in fresh and dry mass accumulation by Chinese cabbage (*Brassica chinensis* L.) plants under combined narrowband red and blue light emitting diodes (LEDs) in comparison with illumination by a broad-spectrum high-pressure sodium lamps (HPSL) of equal photosynthetically active radiation intensity. Analysis of photosynthetic activity, sugar content and composition, antioxidant activity, and membrane peroxidation revealed neither inhibition of nor damage to the photosynthetic apparatus. There was also no detectable oxidative stress and related photoassimilate loss, the source-sink relations were also unimpaired in LED-grown plants. Our findings suggest that the light distribution in the plant canopy might be an essential factor limiting plant growth under the LED light. The results are discussed in view of the role of the radiation in the yellow–green range of the spectrum in driving photosynthesis.

1. Introduction

The idea of using light emitting diodes (LEDs) for growing plant first appeared more than twenty years ago when the first LED lamps became available (Barta et al., 1992; Bula et al., 1991; Olle and Viršile, 2013; Tennessen et al., 1994). The advantage of LEDs in comparison with traditional light sources include high photoelectrical efficiency and optimized narrowband spectrum (albeit only red LEDs were available at that time) overlapping with the maximum of the action spectrum of photosynthesis (McCree, 1972). Nevertheless, the first experiments showed that narrowband (full width at half maximum (FWHM) ca. 20–25 nm) red (peaking at 630–670 nm) illumination is insufficient for healthy growth and development of plants which displayed the impaired photosynthesis (Hogewoning et al., 2010), thin elongated stems and petioles (Cope et al., 2014; Hoenecke et al., 1992; Samuolienė et al., 2011), retarded, reduced or even inhibited flowering (Goins et al., 1997; Heo et al., 2002).

It became clear that red light (RL) should be augmented by some other spectral component, and growing plants using mixed red and blue light (RBL) became widespread. An advantage of blue light (BL) is its overlap with the other local maximum in the action spectrum of photosynthesis (McCree, 1972), hence it might play a regulatory role without any substantial decrease in photosynthetic efficiency.

Abbreviations: APX, ascorbate peroxidase; BL, blue light; Car, carotenoids; Chl, chlorophyll; ETC, electron transport chain; ETR, electron transport rate; FWHM, full width at half maximum; HPSL, high-pressure sodium lamp; LED, light emitting diode; MDA, malondialdehyde; PAR, photosynthetically active radiation; PCBL, polychromatic broadband light; P700, primary donor of photosystem I; PSA, photosynthetic apparatus; PSI and PSII, photosystem I and photosystem II, respectively; ROS, reactive oxygen species; RL, red light; RBL, red plus blue light; SOD, superoxide dismutase; TCA, trichloroacetic acid; TBA, thiobarbituric acid.

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Numerous studies on diverse plant species demonstrated that even a small addition of BL (usually a narrowband BL: FWHM 20–25 nm; λ_{max} 435–470 nm or, in pioneering works, blue fluorescent lamps with wider spectra, 410–510 nm, were used) cancels most of the negative effects of the RL illumination (Brown et al., 1995; Fan et al., 2013; Goins et al., 1997; Lee et al., 2007; Shin et al., 2008; Yorio et al., 2001). Most of the reports demonstrate a monotonous increase in growth with increase of BL proportion of the incident radiation achieving its maximum at 12–20% (or, in some reports, up to 50%) BL. In addition to the positive effect on growth parameters, the admixture of BL to RL improves most of other physiological defects usually observed in RL-grown plants (Cope et al., 2014; Hogewoning et al., 2010; Samuolienė et al., 2011).

Notably, plants grown under RBL possess higher productivity compared with RL or BL as was shown for cucumber (Hogewoning et al., 2010), Chinese cabbage (Fan et al., 2013), radishes, lettuce and pepper (Cope et al., 2014), and for in vitro grown *Doritaenopsis* hort. (Shin et al., 2008) and *Withania somnifera* (Lee et al., 2007).

Some studies, however, showed the opposite effect of augmenting growing illumination with BL for the same plant species (Li et al., 2012; Son and Oh, 2013). The reason of this controversy is not clear albeit it might stem from the delayed RL, BL and RBL treatments (starting from 18th day of growth). Still, the role of conditions (irradiance, photoperiod, temperature, humidity, substrate and nutrient composition) in generation of the contradictory results requires close and comprehensive attention.

Hence augmentation of the energetically most efficient RL with a small amount of BL could be the next step in optimizing the illumination for plant growth. The optimal BL proportion in RBL is expected to be in the range 7–20%. A critical question is if this optimization of narrowband RL by BL addition could be sufficient to ensure normal growth and development of plants.

Available data on this issue are even more controversial than the data concerning RL or BL. Some studies show that RBL growing provides the same or even higher productivity than conventional polychromatic broadband light (PCBL) sources (Bula et al., 1991; Fan et al., 2013; Li et al., 2012). However, many studies showed that RL and BL fail to ensure as high productivity as possible with the conventional PCBL sources (including daylight fluorescent, metal halide, incandescent or high-pressure sodium lamps) (Avercheva et al., 2009, 2014; Brown et al., 1995; Goins et al., 1997; Yorio et al., 2001).

Basing on the data available to the date, one can raise two questions. First, which factors (apart from species-specifics) account for controversial reports on the efficiency of RBL vs. PCBL for growing plants? Second, which factors reduce plant productivity under RBL? This study aimed at finding an answer to the second question.

There are some groups of factors limiting plant productivity:

(i) light acclimation of photosynthetic apparatus (PSA), which may reduce its efficiency of light energy conversion in some environmental conditions. Thus intensive BL caused induction in expression of PSII-core dimer and RuBisCO in lettuce, while RL- and especially green light grown plants were deficient in these proteins (Muneer et al., 2014);

(ii) the systemic plant response, including some kind of stress, end product regulation of photosynthesis and sink limitation (Fatichi et al., 2014; Lawlor, 1995; Paul and Foyer, 2001). Oxidative stress as a result of suboptimal light quality or irradiance (Karpinski et al., 1999; Kreslavski et al., 2012; Vandenabeele et al., 2004) may lead to retardation of plant growth. The oxidative stress in plants is widely probed by a set of conventional markers such as ascorbate peroxidase (APX), superoxide dismutase (SOD) (Bowler et al., 1992; Morita et al., 1999; Sharma et al., 2012; Yoshimura et al., 2000), or malondialdehyde (MDA), a product of fatty acids oxidation and an important player in oxidative stress response of a plant (Shulaev and Oliver, 2006; Weber et al., 2004). These markers were used for characterization of narrow-band light grown plants (Astolfi et al., 2012; Ilieva et al., 2010), which sometimes showed increased level of the oxidative stress markers (Dong et al., 2014; Lee et al., 2007), but the question concerning possible role of oxidative stress in retardation of growth under narrow-band light remains unclear;

(iii) radiation use efficiency, which may decrease due to chloroplast-level changes (e.g., changes in amount and composition of light-harvesting pigments) as well as with the whole canopy-level reasons (Kim et al., 2011; Lichtenthaler et al., 2013; Vogelmann and Gorton, 2014). The idea of different penetration through the leaf of different light spectral components as a substantial factor of photosynthetic productivity has attracted the attention of researchers in recent years due to the works of Vogelmann, Nishio, Terashima and coauthors (Nishio, 2000; Sun et al., 1998; Terashima et al., 2009). Still as far as we know, there are no, if any, applications of this idea to the problem of productivity of narrow-band light grown plants. The attention to the issue was recently paid by researchers (Massa et al., 2015), still this might just become the beginning of discussion.

We tested all the possibilities in the present work.

2. Materials and methods

2.1. Plant material and growth conditions

Experiments were performed with Chinese cabbage (*Brassica chinensis* L.), cv. Vesnyanka bred at the All-Russia Research Institute of Vegetable Crop Breeding and Seed Production. Plants were grown in hydroponic solution on porous cermet 16-mm diameter tubes penetrating fibrous artificial soil (BIONA-V3, Russia) (Berkovich et al., 2003). Water potential at the plant root zone was –1 kPa. Previously we showed that this water potential value is optimal for plants growth and development, ensuring effective accumulation of organic matter (Berkovich et al., 1999) and transpiration from the leaf surface ca. 190 g $H_2O\,m^{-2}\,h^{-1}$, which is comparable with that of *Brassica* species and other C3 plants grown in optimal environmental conditions (Denna, 1970; Kumar et al., 1994; Morison and Gifford, 1984). The mineral solution used was according to Chesnokov (2 times diluted) with some modifications and added Hoagland micronutrients: 5 mM KNO_3, 2.4 mM $Ca(NO_3)_2$, 1.8 mM KH_2PO_4, 0.8 mM $MgSO_4 \times 7H_2O$, 46 μM H_3BO_3, 9 μM $MnCl_2$, 0.8 μM $ZnSO_4$, 0.3 μM $CuSO_4$, 0.1 μM H_2MoO_4, 25 μM iron tartrate (Chesnokov et al., 1960; Hoagland and Arnon, 1950). Air temperature and humidity within the canopy were measured with digital thermometer/hygrometer HC-520 with remote sensor (Shanghai Handsun Electronic Co., Ltd., China), the temperature and relative humidity was maintained at the level of 25 ± 1 °C and 30–55%, respectively.

Control plants were grown under illumination with a DNaT-400 high-pressure sodium lamp (HPSL) fitted with a standard reflector and supplied with phosphate glass filters cutting off infra-red radiation to avoid addition thermal irradiation of plants (Smolyanina et al., 2003). The other plant group (treatment) was grown under a light source of original construction (Erokhin and Berkovich, 2005) with red (λ_{max} = 650 nm) and blue (λ_{max} = 470 nm) LEDs at red/blue photon flux density ratio of 7:1 (Avercheva et al., 2009; Erokhin and Berkovich, 2005). The spectral distribution of the LED and HPSL sources is presented in Table 1.

Plants were grown under continuous light according to our previous data showing that this long-day plant species does