Scientia Horticulturae 200 (2016) 111–118

Contents lists available at ScienceDirect

Scientia Horticulturae

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

# Growth and nutritional properties of lettuce affected by mixed irradiation of white and supplemental light provided by light-emitting diode

Xiao-li Chen[a], Xu-zhang Xue[a,*], Wen-zhong Guo[a,b], Li-chun Wang[a,b], Xiao-jun Qiao[a]

[a] Beijing Research Center for Information Technology in Agriculture, Beijing Academy of Agriculture and Forestry Sciences, Beijing 100097, China
[b] Beijing Agricultural IOT Engineering Technology Research Center, Beijing 100097, China

ARTICLE INFO

*Article history:*
Received 20 July 2015
Received in revised form 3 January 2016
Accepted 7 January 2016
Available online 21 January 2016

*Keywords:*
LED light
Pigment
Soluble sugar
Ascorbic acid
Nitrate

ABSTRACT

'Green Oak Leaf' lettuce were hydroponically cultured for 35 days under mixed light qualities of white light and a different supplemental light such as blue (B), green (G), yellow (Y), red (R), and far-red (Fr) provided by light-emitting diodes (LEDs). Effects of supplemental light qualities on the growth and nutritional properties of lettuce plants were investigated. The pure white LED (W) was used as control with a photosynthetic photon flux (PPF) value of approximately 135 $\mu$mol m$^{-2}$ s$^{-1}$, and the basal white light in each treatment was 105 $\mu$mol m$^{-2}$ s$^{-1}$ while the photon flux added by supplemental LED was approximately 30 $\mu$mol m$^{-2}$ s$^{-1}$. The results indicated that supplemental lights led to obvious morphological changes, plants with WR appeared compact and vigorous while those with WY and WFr looked sparse and twisted, dwarfed plants with large leaves were detected under WB. Compared with those grown in the white light control, the fresh weight of shoots increased by 63.2% and 21.7% with supplemental R and B respectively, while decreased by 35.9% with supplemental Fr. Chlorophyll and carotenoid contents were significantly higher with supplemental R and B than other treatments. Supplemental B and G resulted in decrease of nitrate content. Supplemental G significantly promoted soluble sugar accumulation. Supplemental Fr increased S/R ratio and ascorbic acid accumulation but resulted in lower biomass and pigment contents. However, no positive impact of supplemental Y light was observed in the research.



## 1. Introduction

Light plays a vital role in driving photosynthesis, regulating plant growth and phytochemical biosynthesis (Walters, 2005; Matsuda et al., 2007; Perez et al., 2008). When artificial lights are used, light environment can be adjusted and optimized by proper design and regulation of light conditions, thereby improving growth and quality of horticultural plants (Samuolienė et al., 2012a). It is possible to maximize the economic efficiency of plant production and nutrition potential of vegetables by means of the precise managements of the irradiance and wavelength in controlled environments.

Early types of artificial light source used in protected cultivation were incandescent lamps, metal halide lamps, high-pressure sodium lamps (HPSL) and fluorescent lamps, all of which have wide ranges of wavelengths that are not possible to be positioned for targeted purposes depending on plant cultivars and desired responses (Wheeler, 2008). With the technological development in semiconductor diode, light-emitting diodes (LEDs) have offered new opportunities for protected cultivation and horticultural research. Among a series of advantages such as narrow bandwidth, low heat output, long lifetime, low weight/volume and stroboflash over traditional horticultural lights sources (Okamoto et al., 1996; Ilieva et al., 2010), the capability of spectral composition control is the most highlighted and evolutional superiority for horticultural use. It has been known that light quality affects gene expressions of plants through initiating the signaling cascade of photoreceptors like phytochrome, cryptochrome and phototropins (Lillo and Appenroth, 2001 ; Giliberto et al., 2005). In that individual photoreceptors tend to sense specific regions of the spectrum, effects associated with a specific waveband can be isolated by using narrow-bandwidth LEDs, which is of great significance for plant photobiology research in protected horticulture.

To date, LEDs have been used for decades in plant photophysiology research to test plant responses to narrow-bandwidth light (Morrow et al., 1989). The effects of red and blue radiation

* Corresponding author. Fax: +86 10 51503591.
*E-mail address:* xuexz@nercita.org.cn (X.-z. Xue).

http://dx.doi.org/10.1016/j.scienta.2016.01.007
0304-4238/

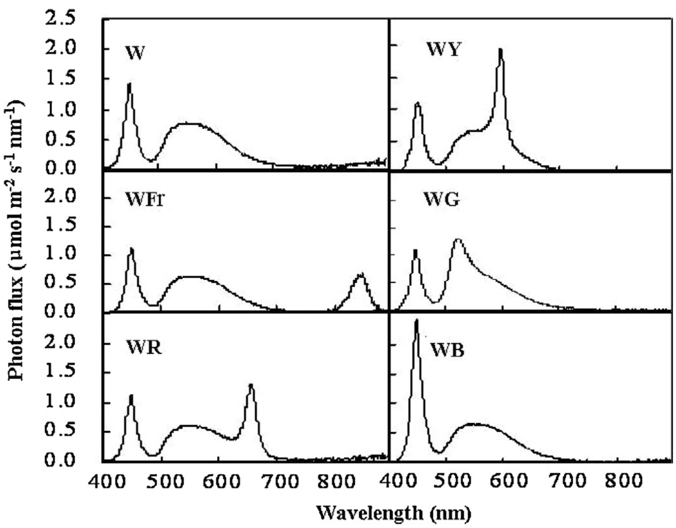


**Fig. 1.** Light spectral of each treatment in the experiments. Abbreviations W-white LED, WFr-white LED plus far-red LED, WR-white LED plus red LED, WY-white LED plus yellow LED, WG-white LED plus green LED, WB-white LED plus blue LED (hereinafter the same).

on plant growth and development constitute much of the focus of past and current researches. Red light has been regarded as the basal lighting spectra for normal plant growth, some researchers suggested that red light was indispensable for the development of the photosynthetic apparatus and affected plant morphogenesis by inducing transformations in phytochrome, red light was also reported to be important in regulating the synthesis of photochemicals such as phenolic and oxalate (Saebo et al., 1995; Furuya, 1993; Qi et al., 2007; Choi et al., 2015). Blue light was important in the chloroplast development, chlorophyll synthesis, stomatal opening and photomorphogenesis, blue light was also reported to be effective wavelengths regulating anthocyanin biosynthesis (Cosgrove, 1981; Senger, 1982; Giliberto et al., 2005; Li et al., 2009). Terashima et al. (2009) reported that green light penetrated and could be absorbed by the chloroplasts in the abaxial side. Green light may participate in the photosynthetic process and have a lot of physiological effects including stimulating early stem elongation antagonizing light-mediated growth inhibition in hypocotyls (Folta., 2004; Bouly et al., 2007). There was sparse literature on yellow light effects on plant growth, scanty analysis conducted by Dougher and Bugbee (2001) suggested that 'yellow' light from 580 to 600 nm suppressed chlorophyll or chloroplast formation in lettuce thus inhibited lettuce growth. Far-red light reverses the status of phytochromes, leading to changes in gene expression, plant architecture, and reproductive responses (Yeh and Chung, 2009). Supplemental far red LED increased growth parameters such as total biomass, stem length, leaf width, while decreased contents of secondary product such as anthocyanin, carotenoids in lettuce (Stutte et al., 2009; Li and Kubota, 2009).

As mentioned above, different monochromic light have various functions in driving physiological process. However, the effects of light quality are complicated and often reported with mixed or even contrary results. Chen et al. (2014) pointed that plant responses to monochromic light might also depend on the remaining spectral composition, that was, light effects differed when other parts of the spectrum varied. Actually, plants in nature are used to utilizing the wide spectrum of sunshine, interdependence as well as interaction exist among different monochromic lights which lead to various functions. Therefore, it is possible that functions of monochromic light quality on plants could be demonstrated more sufficiently and objectively when offered with a relatively wide spectrum such as white LED light.

Terrestrial plants have evolved under a wide spectrum of light, although monochromic light quality may have potential for use as a light source to drive photosynthesis or other physiological processes, plants are adapted to utilize a wide-spectrum of light to control their growth and development (Briggs, 1993; Brown et al., 1995). Lin et al. (2013) claimed greater biomass and soluble sugar content as well as lower nitrate content in lettuce plants cultured under RBW than RB LE Chen et al. (2014) reported that FLR (white fluorescent light plus red LED) and FLB (white fluorescent light plus blue LED) resulted in improved morphology, greater biomass and pigment contents of lettuce than monochromic R, B, FL or RB. These results might indicate that efficiency of R or B light could be manifested when provided with white light as basal light. It can be inferred effects of other monochromic lights on plants can be also better expressed when provided with basal white light.

Here in the study, we chose white LEDs rather than incandescent lamps, metal halide lamps, high-pressure sodium lamps or fluorescent lamps as the provider of wide background spectrum. Besides the inherent advantages of LEDs, white LEDs have greater freedom in spectral design than conventional white light sources. White light from LEDs can be realized by a mixture of multicolor LEDs or by combinations of phosphors excited by blue/UV LED emission from the GaN-based LED chips, in which, phosphor type is more commonly used than multichip type due to higher light efficiency and spectrum controllability (Ohno, 2005). So far there have been several white LED spectra, whose differences for plants mainly lie in the red and far-red spectral proportions of the whole spectrum. The more energy added in the red region of the white LED spectrum, the lower luminous efficacy achieved, because red phosphor is less efficient compared with yellow phosphor (Narendran, 2005). Plants grow normally under sunlight or combined artificial red and blue light (Kim et al., 2004; Ohashi-Kaneko et al., 2007), it seems that most plants can survive under white LED, since white LED light incorporates both red and blue light. Thus, white LED sources that are typically used for general illumination have also been valued for plant cultivation use (Lin et al., 2013). However, there are rarely basis for the spectrum design of white LED used in cultivation.

In this study, using white LED as the basal light source and other LED colors as supplemental light, plant height, biomass, and accumulations of chlorophyll (Chl), carotenoids (Car), soluble sugar, ascorbic acid and nitrate were measured to show lettuce responses to different light quality. The objective of the study presented in this manuscript was to determine the effects of red, blue, green, yellow and far-red light on lettuce based on the same light background, a second objective was to find out one or more efficient supplemental lights to enhance the productive efficiency of white LED light. Simultaneously, we hope the findings can supply possible directions for white LED design.

## 2. Materials and methods

### 2.1. Experimental set-up and growth conditions

After incubated at 4 °C on moistened gauze for 5 d, germinated lettuce seeds (*Lactuca sativa* var.*crispa* 'Green Oak Leaf') were sown in sponge cubes (2.0 cm × 2.0 cm × 2.0 cm) and hydroponically grown in an environmentally controlled growth room. Air temperature, $CO_2$ level, and relative humidity (RH) were maintained at 22/18 °C (day/night), 350 μmol mol$^{-1}$, and 65%, respectively throughout the experiment. Each hydroponic box (80 cm × 80 cm × 10 cm) contained 41.6 L nutrient solution with a liquid level of 6.5 cm, and 36 plants spaced 13 cm apart were planted in each container. The modified half-strength Hoagland's