

Various Light Quality including QD-LED Affect Growth and Leaf Color of Red Romaine Baby Leaf Lettuce

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Abstract

Light quality has a substantial effect on crops in plant factories. Quantum dot (QD) refers to ultrafine semiconductor particles and is expressed in a variety of wavelength ranges and fine and precise colors and is attracting attention as a next-generation material. This study was conducted to investigate the effects of various light qualities, including a QD-LED light source on the growth and color development of red romaine lettuce in the LED chamber system for plant factories. The light source was red fluorescent (FL), blue (B), red (R), blue + red mixed light (BR), and blue + wide range red + red mixed light QD-LED. The growth index, chlorophyll content, and leaf color were examined. The results showed that the plant length was long without a significant difference in QD-LED and the red (R) wavelength and showed the fastest growth under QD-LED. The photosynthetic rate and chlorophyll content were the highest in QD-LED light with a broad spectrum of red light. The leaf colors a^* , b^* , the hue angle, and total anthocyanin content showed the highest in QD-LED light, while b^* and the hue angle values were the lowest. As the light wavelength range was changed, there was a significant difference in the growth response and leaf color, and it is considered that QD-LED light should be considered positively when applied to plant factories.

Keywords: anthocyanin; chlorophyll; hue angle; photosynthetic rate; plant factories

Introduction

The recent increase in the demand for convenient and healthy foods resulted in consumer interests in baby leaf vegetables, which are ready-to-eat (Santos *et al.*, 2014). Baby leaf vegetables that have been in demand in recent years include lettuce, spinach, rocket, lamb's lettuce and Swiss chard (Fallove *et al.*, 2009).

Lettuce has been widely used for research on baby leaf vegetables (Samuolienė *et al.*, 2013; Jung, 2015) and hydroponics and environmental control research (Kang *et al.*, 2016) because of its various shapes, colors and short growth period. In particular, lettuce has been used for research related to the light quality using artificial light

sources in a closed plant factory environment due to the low light saturation point (Cha *et al.*, 2013). The light quality of the artificial light in a closed plant factory has an important role on the quality and growth of crops (Lin *et al.*, 2013). When lettuce was cultivated in various lights using a light emitting diode (LED), blue light influenced the growth of lettuce (Johkan *et al.*, 2010), and the anthocyanin content of red leaf lettuce was affected, depending on the wavelength of the LED lights (Lee *et al.*, 2010).

LED lights mainly used in existing studies on light quality are being used in plant factories; however, the high installation price, which results in a high early investment cost and high heat radiation of the LED lights, are problematic (Matsumoto *et al.*, 2010). Recently, a quantum dot light source, which has a lower installation cost and

power consumption compared to existing LED lights, has been introduced (Yoo *et al.*, 2018). QD-LED (quantum dot-light emitting diode) lights have multiple wavelengths, high color purity, light stability, and high quantum efficiency characteristics, is based on color conversion used to convert the blue light from LED chips into different colors (Hang and Yang, 2017). These properties explain this light source's study and application in many areas (Hang and Yang, 2017).

However, research as a light source for plant cultivation is still insufficient. This study aimed to find the practical use of QD-LED light sources in plant factories using artificial light sources and basic data on producing high quality leafy vegetables by comparing the growth and quality of red romaine baby leaf lettuce under different light sources, which include QD-LED light sources.

Materials and Methods

Plant materials and growth conditions

Lettuce (*Lactuca sativa* L. 'Red Romaine') was sown in a plug tray (128 hole) containing a horticultural commercial substrate mix (Baroker, Seoul Bio, Korea) and was grown in a climate chamber established with supplemental light equipment described below for 6 weeks. The air temperature was controlled to a 23/18 °C day/night cycle; the relative humidity was 70%, and the carbon dioxide concentration was ambient.

Characteristics of light sources and light spectral analysis

The light treatments consisted of an irradiance provided by cool white fluorescent lamp (5DULUX D FDX 18EX-D, OSRAM, Korea), 10 W LED lights (Cheorwon Plasma Research Institute, Korea) with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and 10 W QD-

LED lights (Cheorwon Plasma Research Institute, Korea) with B+WR+FR (peak at 450 and 650~720 nm). The lights were placed 15 cm above the plant canopy horizontally inside the climate chamber. The average W, B, R, B+R and R+WR+PF added by the supplemental light intensity (photosynthetic photon flux density) was 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The illumination of the main light sources and supplemental light sources was for 16 h per day in all of the treatments. The spectrum and intensity of the light sources used as treatments were measured using a spectroradiometer (HD2102.1, Delta OHM, Italy) and a quantum sensor (HD2102.1, Delta OHM, Italy) at the plant canopy levels (Fig. 1 and Table 1).

Analysis of growth, colour, chlorophyll and anthocyanin

Every 7 days after initiating supplemental light treatments (26 days after sowing), 10 plants were measured separately for measurements of plant growth, such as plant height, leaf length, and leaf width. Fresh weight, dry weight, leaf color, leaf chlorophyll concentration, and anthocyanin content were measured for five plants selected from each treatment at 6 weeks after the light treatments. The leaf chlorophyll concentration and leaf color were measured using SPAD (502Plus, Konica Minolta, Japan) and a colorimeter (CR-400, Knika Minolta, Japan), respectively. Total anthocyanin content was measured as described by Park *et al.* (2012). The 530 nm absorbance wavelength of a UV spectrophotometer (Shimadzu Corporation, Tokyo, Japan) was used. Each 2 g leaf sample was extracted after 24 h of 4 °C in the dark using 10 mL of 1.5 N HCl-95% ethanol (85:15, v:v). Total anthocyanin was calculated using the following formula:

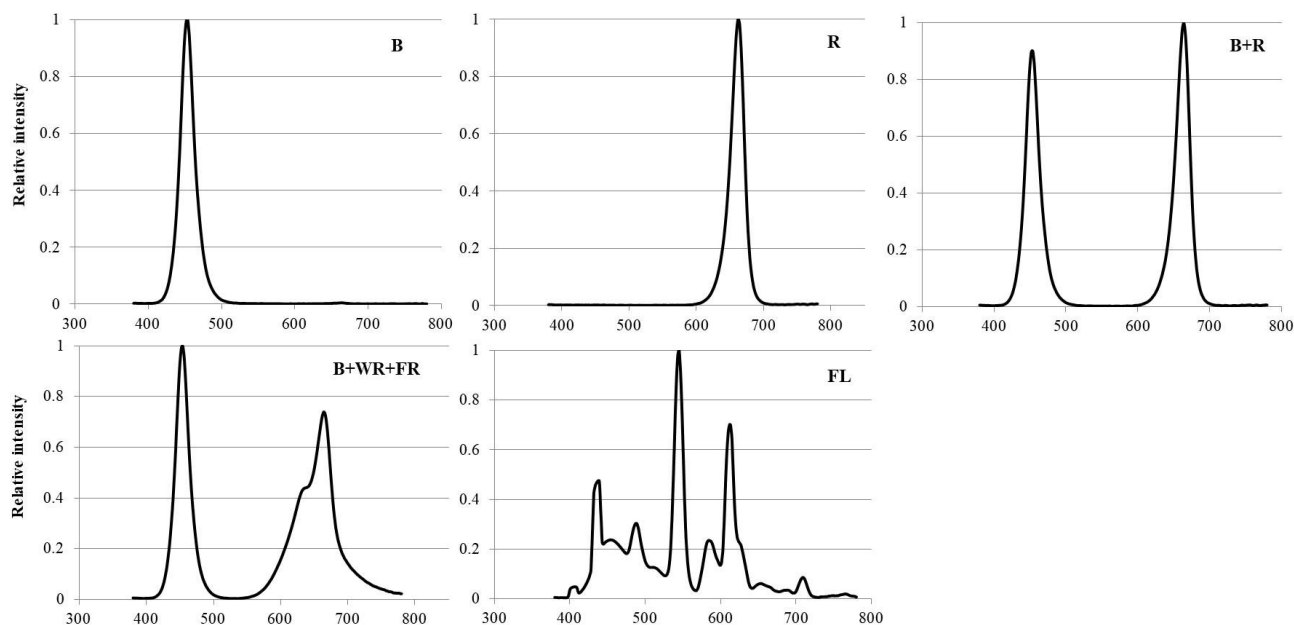
$$\text{Anthocyanin (mg/100 g fresh wt.)} = (\text{absorbance at 530 nm} \times \text{volume of extraction solution} \times 100) / (\text{wt. of sample of g} \times 98.2).$$


Fig. 1. Relative spectral distribution of the LEDs (B, R, B+R), QD-LED(B+WR+FR) and FL(cool white fluorescent lamp) used in this study. Photosynthetic photon flux was about 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ in each treatment. Spectral scans were recorded at the top of the pots and averaged at 5 points of each treatment

Table 1. Spectrum wavelength ratio (%) of light quality treatments measured on the growth bed bottom under 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity (Photosynthetic Photon Flux Density)

Spectrum wavelength	Light quality treatments ^z				
	FL	B	R	B+R	B+WR+FR
Blue (430-480 nm)	22.3	93.3	0.3	44.0	34.6
Green (520-570 nm)	26.5	0.2	0.1	0.2	0.6
Red 1(600-670 nm)	23.4	0.3	82.3	41.9	41.0
Red 2 (671-700 nm)	1.5	0.0	15.4	10.0	11.4
Far-red (700-780 nm)	3.1	0.0	1.2	0.7	6.6

^zLight quality treatments were a cool white fluorescent lamp, 10 W LED lights with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and a 10 W QD-LED light with B+WR+FR (peak at 450 and 650~720 nm).

Measurement of photosynthetic rate, transpiration and stomatal conductance

At 25 days after sowing, the photosynthetic rate, transpiration and stomatal conductance were measured from five typical fully expanded canopy leaves per light treatment using a portable photosynthetic meter (model LI-6400xt, LI-COR Inc., USA) and steady state porometer (model LI-1600, LI-COR), respectively. The conditions of measurements were 150 $\mu\text{mol}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ light intensity, 22.5°C leaf temperature, 400 $\mu\text{mol}\cdot\text{m}^{-2}$ of carbon dioxide concentration, and 500.5 $\mu\text{mol}\cdot\text{s}^{-1}$ flow rate, and RH 55%.

Statistical analysis

Statistical analyses were performed using SPSS (IBM SPSS Statistics version 22, SPSS Inc., Chicago, IL) statistical program. Duncan's one-way ANOVA was used to analyse the significance according to light quality treatments at significance level 0.05. The mean separations were conducted using Microsoft Excel 2010 (Microsoft Co., USA).

Results and Discussion

Growth characteristics

The growth of red romaine based on the light quality was different depending on growth factors, such as plant height, leaf length and leaf width. The plant height was longer in the red light (R) and QD-LED light (B+WR+FR) and shorter in the blue light (B) and fluorescent light (FL) treatments during the light treatment

period. The leaf length and leaf width were higher in the order of the QD-LED light (B+WR+FR) and mixed light (B+R), and fluorescent light (FL), which had the shortest leaf length, at 36% of QDLED light and red light (R), with the narrowest leaf width using only 27% of the QD-LED light. Li and Kubota (2009) also reported that far-red light promotes the growth of the leaves and leaf width, and QD-LED light containing far-infrared light has the best growth.

The growth of the upper part of the lettuce is promoted by the red light (R), and the blue light (B) suppressed growth (Lee *et al.*, 2010). In addition, it is more efficient to promote photosynthesis by irradiating red light and blue or far-red lights for growth, rather than using a single wavelength light (Ouzounis *et al.*, 2015).

The leaf shape was measured to investigate the effect of the light source on the morphological development of red romaine lettuce. However, in the late stage of growth, red leaf (R) promoted only the leaf length and showed a much higher leaf shape index (Fig. 3). It has been reported that the plant length of the 'Lollo rosa' lettuce was longer in the red light condition (Shin *et al.*, 2012), and the light quality has been reported to act not only as an energy source for plant growth, morphogenesis, and pigmentation but also as a regulator (Fankhauser and Chory, 1997). The shoot fresh weight at the end of cultivation was the heaviest in the QD-LED light treatment and mixed light (B + R) followed by red light (R), blue light (B) and fluorescent light (FL). In addition, the shoot dry matter ratio was the highest in QD-LED light, and there was no significant difference among the other light sources (Table 2).

Table 2. Top fresh weight, top dry matter ratio, photosynthetic rate, stomatal conductance, and transpiration rate of red romaine grown in each light quality treatment

Light quality treatments ^z	Top Fresh weight (g)	Top dry mater ratio (%)	Photosynthetic rate ($\mu\text{mol}\cdot\text{CO}_2\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Stomatal conductance ($\text{mol}\cdot\text{H}_2\text{O}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)	Transpiration rate ($\text{mol}\cdot\text{H}_2\text{O}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$)
FL	0.53 b ^y	4.61 b	3.17 d	0.06 a	1.72 ab
B	0.67 b	4.91 b	4.96 bc	0.07 a	1.78 ab
R	0.76 b	3.35 b	3.81 cd	0.04 a	1.18 b
B+R	1.10 a	5.39 b	6.12 b	0.07 a	2.02 ab
B+WR+FR	1.19 a	8.31 a	7.35 a	0.08 a	2.56 a

^zLight quality treatments were a cool white fluorescent lamp, 10 W LED lights with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and a 10 W QD-LED light with B+WR+FR (peak at 450 and 650~720 nm).

^yMean separation of columns by Duncan's multiple range tests at $p \leq 0.05$.

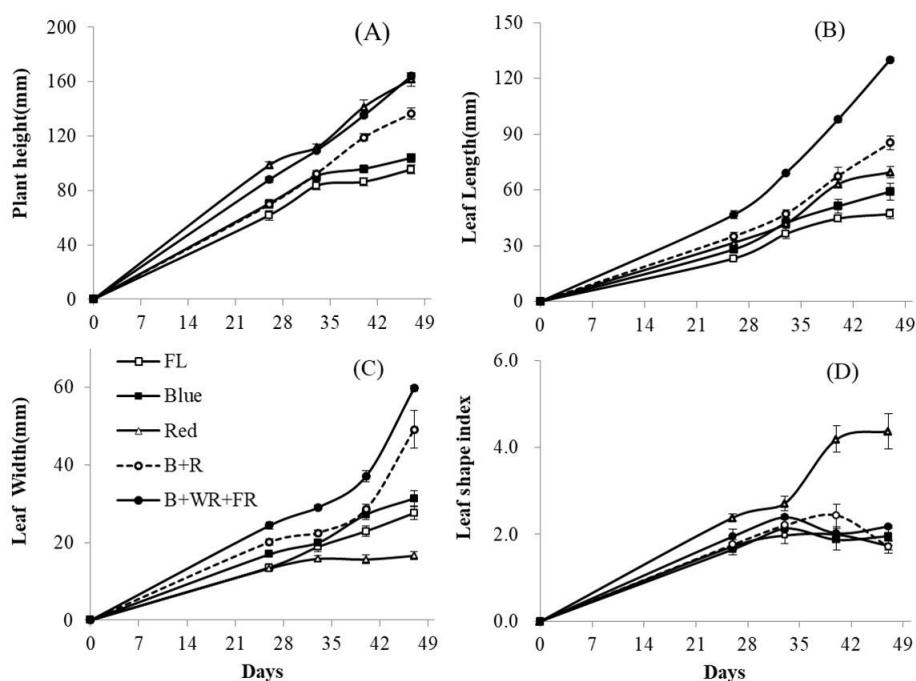


Fig. 2. Change of plant height(A), leaf length(B), leaf width(C), and Leaf shape(D) of red romaine grown in each light quality treatments which were a cool white fluorescent lamp, 10 W LED lights with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and a 10 W QD-LED light with B+WR+FR (peak at 450 and 650~720 nm). The data represent the means and the vertical bars indicate standard errors (n=10)

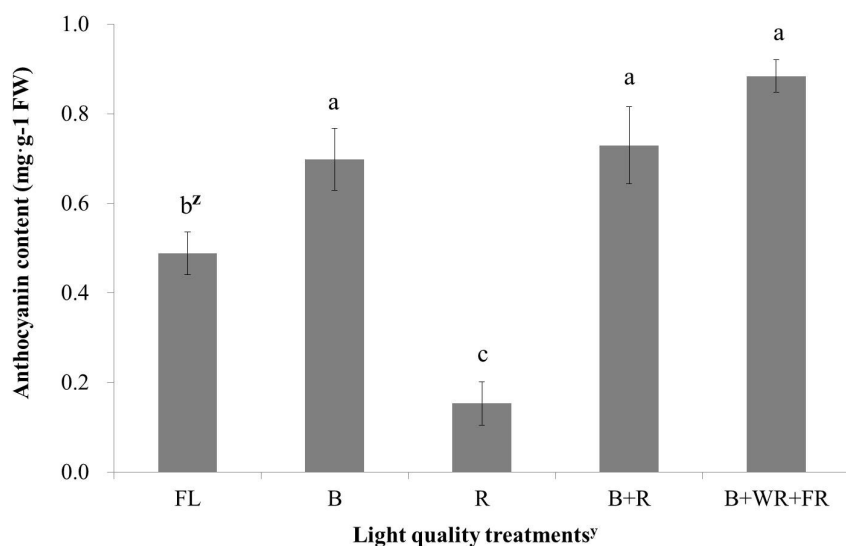


Fig. 3. Total anthocyanin content of red romaine grown in each light quality treatments. The data represent the means and the vertical bars indicate standard errors (n=5). ^zMean separation of treatments by Duncan's multiple range tests at $p \leq 0.05$. ^yLight quality treatments were a cool white fluorescent lamp, 10 W LED lights with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and a 10 W QD-LED light with B+WR+FR (peak at 450 and 650~720 nm)

Comparison of photosynthetic rate, transpiration and stomatal conductance

The photosynthetic rate at 25 days after sowing was the highest in the QD-LED light and the lowest in the fluorescent light (FL) and red light (R). The transpiration rate was the highest in the QD-LED and the lowest in red light (R). However, the stomatal conductance did not show any statistical significance among the treatments (Table 2).

The photosynthetic rate of plants is affected by the light

quality, but the mixed light sources of these were much higher than the red or blue monochromatic light (Matsuda *et al.*, 2007; Savvides *et al.*, 2012).

In addition, the highest photosynthetic rate is observed with the QD-LED light because the QD-LED light simultaneously irradiated blue and red, which are effective for photosynthesis and red external light and can expect an Emerson enhancement effect (Govindjee and Govindjee, 1964). In addition, Li and Kubota (2009) reported that far-

red was effective at increasing the growth of lettuce. In this experiment, the final growth index of the QD-LED light was the highest, and the photosynthetic rate was also significantly higher.

Color and phytochemical contents

The chlorophyll content (SPAD) was the highest in the QD-LED light at the end of cultivation and the lowest in the fluorescent light (FL) and red light (R) (Table 3). Wongnok *et al.* (2008) reported that the light quality affects the chlorophyll content of lettuce and that the blue light is related to the chlorophyll accumulation in the leaves. The higher the ratio of the blue light is, the higher the chlorophyll content is (Hogewoning *et al.*, 2010; Johkan *et al.*, 2010). In this experiment, the chlorophyll content was low in fluorescent light (FL) and red light (R), which have a relatively low proportion of blue light, and showed similar results as the previous study.

The a^* value of the leaf, which indicates the red colour as the value increases in green, was the highest in the QD-LED light and the lowest in the red light (R), and the b^* value indicating blue to yellow was the highest in the red light (R) and the lowest in the QD-LED light. In addition, the hue angle value was the lowest in the QD-LED light (Table 3). The anthocyanin content of red romaine was reported to

increase with lower hue angle and higher SPAD (Gazula *et al.*, 2007; Lee and Kim, 2014). In this experiment, total anthocyanin content was significantly higher in the QD-LED light, which had a lower hue angle and a higher SPAD value than other treatments. Alternatively, it was lowest in the red light (R) and was more than 5 times larger in the QD-LED light. Nishimura *et al.* (2006) reported that the anthocyanin content is increased when two light sources of red light and blue light are mixed. In this experiment, it was higher in the QD-LED light and the (B + R) mixed light that were mixed with blue and red light. Therefore, it was determined that the QD-LED light is more effective for the red coloration of red romaine lettuce than for the other light sources, and Lee *et al.* (2010) reported that the growth of the lettuce and the content of the pigment could be controlled simultaneously based on the light quality of the LED light source. As described above, there was a significant difference in the growth and leaf colour of the red romaine baby leaf lettuce based on the change of the light wavelength, and the growth and red colouring were effective in the mixed light source of the red wavelength with the near infrared wavelength and the blue (B) light source. Therefore, the QD-LED light with a mixed wavelength band shows promise for application in plant factories to produce baby leafy vegetables.

Table 3. Chlorophyll and Leaf color (Hunter a^* , b^* , and hue angle) of red romaine grown in each light quality treatment

Light quality treatments ^a	Chlorophyll (SPAD)	Leaf color(value)		
		Hue angle	a^*	b^*
FL	19.26 c ^b	125.07 a	-10.889 b	15.084 b
B	22.06 bc	122.48 a	- 8.481 b	12.907 b
R	21.28 c	127.93 a	-18.079 c	23.237 a
B+R	25.64 ab	123.98 a	- 8.556 b	12.358 b
B+WR+FR	28.34 a	109.00 b	- 3.841 a	8.259 c

^aLight quality treatments were a cool white fluorescent lamp, 10 W LED lights with B (peak at 450 nm), R (peak at 660 nm), B+R (peak at 450 + 660 nm), and a 10 W QD-LED light with B+WR+FR (peak at 450 and 650~720 nm).

^bMean separation of columns by Duncan's multiple range tests at $p \leq 0.05$.

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