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Influence of blue/red vs. white LED light treatments on biomass, shoot morphology, and quality parameters of hydroponically grown kale

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ABSTRACT

Solid-state light emitting diodes (LEDs) are emerging as an energy efficient alternative lighting source in controlled environments. The objective of this study was to examine the impact of sole-source LED lighting quality/duration on biomass, morphology, and nutritional quality of kale (*Brassica oleracea* var. acephala) in a controlled environment. 'Premier' kale seedlings were grown hydroponically using a 30 d production cycle. Experimental LED treatments included: 1) white LED for 37 d; 2) 5% B/95% R for 37 d; 3) 20%B/80%R for 30 d; 4) 20%B/80%R for 25 d; 5) 20%B/80%R for 20 d; and 6) 20%B/80%R for 15 d prior to harvest. Treatments were arranged in a randomized complete block design, and three complete experimental runs were conducted. Plant height (cm), leaf length and width (cm), shoot and root fresh mass (g) and dry mass (g) were collected at harvest. Kale shoot tissues were measured for nutritionally important pigments, glucosinolates, mineral elements, and soluble carbohydrates. All plants treated with 20%B/80%R lighting were shorter compared to the white (37 d) and 5% B/95%R (37 d) treatments, respectively. Chlorophyll fluorescence parameters were influenced by LED treatment, while maximum quantum yield (QY_{max}) was not. LED light treatment impacted kale zeaxanthin ($P = 0.01$), antheraxanthin ($P = 0.01$), fructose ($P = 0.03$), and potassium ($P = 0.02$). Data suggest that increasing blue light during production has limited impact on 37-d old hydroponic kale developmental and nutritional parameters over continuous white LED lighting.

1. Introduction

The light environment influences critical developmental and phytochemical pathways in plants. Specialized pigment-proteins called photoreceptors are able to perceive incoming solar radiation to signal developmentally appropriate photomorphogenic responses to help plants adapt to changes within their light environment (Kong and Okajima, 2016). These light signals can prompt a diverse range of developmental responses like germination, cotyledon expansion, chloroplast development, stem elongation, root and leaf growth, along with senescence and flowering (Montgomery, 2016). Photoreceptors are able to sense the intensity of light and signal chloroplast movement and gene expression accordingly (Li et al., 2009). Cryptochromes and phototropins are blue and UV-A light photoreceptors, while phytochromes are red and far red light photoreceptors (Dai Yin and Hong Xuan, 2010).

Plant responses to blue light include circadian rhythms, phototropism, stomatal opening, compact growth, and the intracellular positioning of chloroplasts to increase light absorption (Christie et al., 2014). Plant responses to red light from phytochromes include shade avoidance, cell elongation, seed germination, reproductive development, and the development of a greater leaf surface area (Pierik and de Wit, 2013). Light emitting diodes (LEDs) allow for the specific targeting of wavelengths, high intensity, and the unique combination of blue, red, yellow, orange, ultra-violet (UV), and far-red light (Darko et al., 2014). Red light (650–665 nm) satisfies the peak absorption spectrums of chlorophyll and phytochromes, while blue light normalizes the developmental responses triggered by signals from phototropins and cryptochromes (Darko et al., 2014). Red and blue wavelengths provide targeted energy to pigments (chlorophyll and secondary pigments or receptors) involved in photosynthetic CO_2 fixation and basic metabolism; therefore, red and blue wavelengths have the greatest influence on plant growth and development (Massa et al., 2015; Muneer et al., 2014).

In addition to influencing plant growth and development, the light

Abbreviations: ANT, antheraxanthin; BC, β-carotene; Chl*a*, chlorophyll *a*; Chl*b*, chlorophyll *b*; DM, dry biomass; FM, fresh biomass; *Fo*, chlorophyll minimum fluorescence; *Fv*, variable fluorescence; *Fm*, chlorophyll maximum fluorescence; GS, glucosinolate; HPLC, high-performance liquid chromatography; LUT, lutein; NEO, neoxanthin; QY_{max} (*Fv/Fm*), maximum quantum yield; VIO, violaxanthin

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LED Treatment	Exposure Duration (d)						
	7	5	5	5	5	5	5
White – 37 d	White						
5%B/95%R – 37 d	5%B/95%R						
20%B/80%R – 30 d	5%B/95%R	20%B/80%R					
20%B/80%R – 25 d	5%B/95%R		20%B/80%R				
20%B/80%R – 20 d	5%B/95%R			20%B/80%R			
20%B/80%R – 15 d	5%B/95%R				20%B/80%R		

Fig. 1. LED quality and duration treatment design for hydroponically grown 'Premier' kale (*B. oleracea* var. acephala). All LED treatments had an intensity of 250 ± 10 μmol $m^{-2} s^{-1}$; percentages indicate the contribution of blue (B) and red (R) light to total intensity, with duration indicated (d).

environment is able to signal photoreceptors to adjust the accumulation or allocation of different pigments and other photo-protective molecules in response to changes in light quality and intensity (Ouzounis et al., 2015). Carotenoids are associated with proteins in chloroplasts where they act as accessory pigments to transfer a broader range of spectral energy to chlorophyll to promote photosynthesis (Cazzonelli, 2011). To ensure that incoming solar energy does not damage photosynthetic apparatus within chloroplasts, carotenoids quench triplet chlorophyll, release excess energy through non-photochemical quenching (NPQ) via the xanthophyll cycle, and scavenge radical oxygen species (ROS) in cooperation with other antioxidants like ascorbate and tocopherols (Cazzonelli, 2011). These strong antioxidants protect both plants and consumers by quenching free radicals that can damage cell membranes and proteins, aiding in the prevention of cancer as well as other chronic diseases (Slavin and Lloyd, 2012). Purposeful manipulation of the light environment to promote the accumulation of carotenoids and other antioxidants can increase the nutritional value of specialty leafy greens, benefiting consumer health (Liu, 2013).

Vegetables in the Brassica genus often contain glucosinolates (GS) within shoot and reproductive tissues (Wu et al., 2009). Glucosinolate concentration is highly impacted by environmental conditions and can change depending on variety, climate, type of cultivation, type of tissue, developmental stage, and fertility (Charron et al., 2005a,b; Charron and Sams, 2004; Johnson, 2002). Glucosinolates can be hydrolyzed by either myrosinase in Brassica, or β-thioglucosidases in gut bacteria to form different breakdown products such as indoles, isothiocyanates (ITC), and nitriles (Navarro et al., 2011). Glucosinolates can help protect against the development of certain cancers and other diseases primarily through their breakdown products, especially ITC (Fahey et al., 2012). The ITCs can induce apoptosis and immobilize the cell cycle, preventing or limiting carcinogenesis in animal models and in vitro (Wu et al., 2009).

Kale (*Brassica oleracea* var. acephala) is a member of the Brassica genus, which is composed of distinct plants used around the world in mild-weathered regions for different economic purposes. Kale contains a diversity of nutrients including flavonoids, GSs, and carotenoids; many of which can be manipulated through changes in the environment (Schmidt et al., 2010). Previous studies have looked at the impact of LED lighting within the early developmental stages of leafy vegetables, whereas this study examines the impact of LED lighting at a later vegetative growth stage (Bian et al., 2015; Lefsrud et al., 2008). The objective of this study was to examine the impact of duration and light quality of narrow-band wavelength LEDs on the biomass, root and shoot morphology, and nutritional quality of hydroponically grown kale in a sole-source lighting controlled environment.

2. Materials and methods

2.1. Plant production and growing conditions

'Premier' kale (Johnny's Selected Seeds, Winslow, ME) was grown hydroponically in Oasis® Horticubes® for a total of 37 d after emergence (Smithers-Oasis Company, Kent, OH). The Premier kale cultivar was selected due to its prostrate leaf angle and compact growth habit. Kale seeds were presoaked in deionized (DI) water for 24 h and germinated in a refrigerated incubator (Thermal Fisher Scientific, Waltham, MA) at 24 ± 1 °C for 72 h in the dark. The germinated seeds were then transferred to growth chambers at 22 ± 1 °C (Model E15; Conviron, Winnipeg, Manitoba, Canada).

Plants were given a 7 d acclimation period within the growth chambers in solid bottom trays (26 × 52 × 6 cm) filled with DI water. Plants were acclimated either under white LED panels or under 5% Blue (B; 447 ± 5 nm, full width half maximum (FWHM) = 20 nm)/95% Red (R; 627 ± 5 nm, FWHM = 20 nm) LED panels at an average light intensity of 250 ± 10 μmol $m^{-2} s^{-1}$ (Orbital Technologies, Madison, WI) according to their light treatment. After the 7 d acclimation period, seedlings were then transplanted into 10 L tubs containing a nutrient solution (#2 solution; Hoagland and Arnon, 1950). After transplanting, plants were grown using a 30 d production cycle under different LED light treatments.

Except for the white LED treatment, all other treatments were exposed to 5%B/95%R LED for 7 d before the individual treatment was applied to the kale at their respective treatment times. Experimental LED quality and duration treatments included: 1) white LED for 37 d; 2) 5% B/95% R for 37 d; 3) 20%B/80%R for 30 d; 4) 20%B/80%R for 25 d; 5) 20%B/80%R for 20 d; and 6) 20%B/80%R for 15 d prior to harvest (Fig. 1). All LED treatments had an intensity of 250 ± 10 μmol $m^{-2} s^{-1}$; percentages indicate the contribution of blue (B) and red (R) light to total intensity. A randomized complete block design was used. Complete experimental runs were conducted a total of three times, with light treatments within chambers randomized during each run. Plant height (cm), leaf length (cm), and leaf width (cm) were measured just prior to harvest. Shoot tissues were separated from root tissues and both were measured for fresh mass (FM; g) and dry mass (DM; g) at harvest. Fresh shoot tissue samples were stored at −20 °C (± 1 °C) prior to lab analyses.

2.2. Kale shoot tissue chlorophyll fluorescence measurements

Chlorophyll fluorescence parameters were measured just prior to harvest. After a dark acclimation period of 60 min, the center of the third most recently expanded leaf was measured for chlorophyll fluorescence parameters using a hand-held modulated fluorometer (OS30p +; Opti-Sciences, Inc., Hudson, NH). Measurements started with dark-adapted leaf tissues characterized by a low, minimum fluorescence emission signal (F_o). Leaf tissues were then exposed to a strong flash of red light (660 nm; 3000 μmol $m^{-2} s^{-1}$ for 1 s) that transiently reduces