horticulturae

MDPI

Communication

Sole-Source LED Lighting and Fertility Impact Shoot and Root Tissue Mineral Elements in Chinese Kale (*Brassica oleracea* var. *alboglabra*)

T. Casey Barickman [1,*], Dean A. Kopsell [2], Carl E. Sams [3] and Robert C. Morrow [4]

[1] North Mississippi Research and Extension Center, Mississippi State University, Verona, MS 38879, USA
[2] Department of Environmental Horticulture, University of Florida, Gainesville, FL 32611, USA; dean.kopsell@ufl.edu
[3] Department of Plant Sciences, The University of Tennessee, Knoxville, TN 37996, USA; carlsams@utk.edu
[4] Sierra Nevada Corporation, Madison, WI 53717, USA; robert.marrow@sncorp.com
* Correspondence: t.c.barickman@msstate.edu; Tel.: +1-(662)-566-8001

Received: 29 April 2020; Accepted: 15 July 2020; Published: 18 July 2020

Abstract: The current study investigated the impacts of light quality and different levels of fertility on mineral nutrient concentrations in the shoot and root tissues of Chinese kale (*Brassica oleracea* var. *alboglabra*). "Green Lance" Chinese kale was grown under: (1) fluorescent/incandescent light; (2) 10% blue (447 ± 5 nm)/90% red (627 ± 5 nm) light emitting diode (LED) light; (3) 20% blue/80% red LED light; and (4) 40% blue/60% red LED light as sole-source lighting at two different levels of fertility. All plants were harvested 30 days after seeding and shoot and root tissues were analyzed for mineral nutrients. Lighting and fertility interacted to influence kale shoot and root mineral nutrient concentrations. The results indicate that sole-source LED lighting used in production can impact the mineral nutritional values of baby leafy greens now popular for the packaged market. This is evident in the current and previous studies in which lighting affects biomass and indirectly affects mineral nutrient concentrations.

Keywords: blue light; calcium; iron; magnesium; potassium; red light

1. Introduction

Inorganic elements participate in many different mechanisms in plant photosynthesis. Some elements participate in the structure of the photosynthetic apparatus, while others play vital roles in the translocation of photosynthetic products and sink tissue formation (fruits, grains, and storage organs) [1]. Elements can be considered to have direct effects on photosynthesis when deficiencies of a particular element cause a rapid decline in photosynthetic activity. The direct effects of elemental deficiencies are usually considered reversible as reintroduction at a proper level results in the resumption of photosynthetic activity. Indirect effects are not usually readily reversible. The indirect effects occur over a more extended period of time and involve elements not necessarily critical in the photosynthetic process. Instead, they are crucial in the production of metabolites or organs that are directly involved in photosynthesis. The chlorophyll loss and necrosis that accompany an elemental deficiency result in reduced leaf area, biomass accumulation, and metabolic activity. The symptoms of many elemental deficiencies are simply the visual manifestations of decreased photosynthetic activity [2], which have impacts on light utilization and photosynthetic efficiencies, which may lead to decreased mineral nutrient uptake.

Only a small percentage of solar spectral irradiance is captured by chlorophyll *a* and used in photosynthesis. Maximum light absorption by chlorophyll pigments and quantum yield of

photosynthesis occurs primarily in the blue and red regions of the visible light spectrum [3]. Light-harvesting complexes composed of accessory pigments (chlorophyll *b*, lutein, and β-carotene) improve light-harvesting efficiency in the photosynthetically active radiation (PAR) spectrum and direct the flow of excitation energy to the reaction centers [4]. However, the absorption of excess light energy has the potential to damage photosynthetic machinery, and accessory pigments also play an important role in photoprotection [5]. Damage to the photosynthetic apparatus by light intensity or quality (such as high ultraviolet light) will impact the production of metabolites and ATP used to drive elemental ion uptake and flux.

Light influences the concentrations of plant elements by impacting the amount of enzymatic activities associated with uptake within primary metabolic pathways [6]. The absorption of PAR by photosystems I and II (PSI and PSII) results in H^+ ion fluxes within the thylakoid, which need to be counterbalanced by fluxes of other cations. The generation of ATP in the light reactions of photosynthesis becomes a source of energy for active ion movements [7]. Translocated carbohydrates are required for root respiration, which provides the energy needed for active uptake mechanisms [8]. Recent research has demonstrated that shoot tissue elemental concentrations can be impacted by both light quality and light intensity. Specialized photoreceptors in plants called phototropins change metabolic homeostasis and mobilize Ca^{2+} in response to blue light [9]. Kopsell et al. demonstrated that blue/red light emitting diode (LED) lighting ratios in a sole-source light environment acted to increase sprouting broccoli (*Brassica oleracea* var *italica*) microgreen (21 day old) shoot tissue concentrations of mineral nutrients as compared to broad-spectrum incandescent/fluorescent lighting [10]. Changing the light quality environment from blue/red light to only blue, and concomitantly reducing the light intensity from 350 μmols/m^2/sec (blue/red LED) to 41 μmols/m^2/sec (blue LED), for 5 days pre-harvest acted to increase macro-element and micro-element concentrations in sprouting broccoli microgreens significantly [11]. Increasing the photosynthetic photon flux density (PPFD) from 200 to 400 μmols/m^2/sec resulted in increased concentrations (μg/mg) of B, copper (Cu), Fe, Mn, and Zn in a variety of tropical legume cover crops [12].

Our hypothesis is that the concentration of mineral elements in the shoot and root tissues of 30-day-old (baby) leafy specialty vegetable crops will be higher under narrow-band LED light as compared to full-spectrum fluorescent/incandescent light in controlled environments. Because of the increases in shoot tissue mineral elements of 21-day old sprouting broccoli microgreens grown under LED lighting in previous studies [10,11], the objective of this study was to measure the impact of different ratios of blue/red LED light on shoot and root tissue mineral elements in baby Chinese kale (*B. oleracea* var. *alboglabra*).

2. Materials and Methods

2.1. Chinese Kale Culture and Harvest

"Green Lance" Chinese kale (Johnny's Selected Seeds, Winslow, ME, USA) was seeded into growing cubes (Oasis® Hortcubes®, Smithers-Oasis North America, Kent, OH, USA) and grown in controlled environment chambers (Model E15; Conviron, Winnipeg, Manitoba, Canada) at the University of Tennessee, Knoxville, TN. Seeds were cultured at an air temperature of 23 °C with a 16 h photoperiod using a light intensity of 250 μmols/m^2/sec from fluorescent and incandescent bulbs. Five days after germination, seedlings were fertilized with a complete nutrient solution with the elemental concentrations (mg/L) N (52.5), P (7.7), K (58.7), Ca (40.1), Mg (12.3), S (16), Fe (0.25), B (0.12), Mo (0.003), Cu (0.005), Mn (0.12), and Zn (0.012). After 15 days, six seedlings were transferred to 10 L plastic containers (Rubbermaid Inc., Wooster, OH, USA). Six plants were placed into 2 cm round holes set at 10.6 cm × 9.5 cm spacing on each container lid to constitute an experimental unit. The plants were grown in 9 L of a modified nutrient solution [13]. The ⅓ strength Hoagland's nutrient fertility treatment (solution #2) elemental concentrations were (mg/L): N (52.5), P (7.7), K (58.7), Ca (40.1), Mg (12.3), S (16), Fe (0.25), B (0.12), Mo (0.003), Cu (0.005), Mn (0.12), and Zn (0.012). The ½ Hoagland's

nutrient fertility treatment elemental concentrations were (mg/L): N (105.0), P (15.5), K (117.3), Ca (80.2), Mg (24.6), S (32.0), Fe (0.5), B (0.25), Mo (0.005), Cu (0.01), Mn (0.25), and Zn (0.025). The nutrient solutions were aerated with standard aquarium air pumps connected to air stones via plastic tubing. Plants were grown under ¼ or ½ strength Hoagland's nutrient solutions [13] to establish any possible light by experimental fertility interactions.

Kale plants were grown under four different light treatments which consisted of: (1) fluorescent/incandescent light; (2) 10% blue (447 ± 5 nm, full width half maximum (FWHM) = 20 nm)/90% red (627 ± 5 nm, FWHM = 20 nm); (3) 20% blue/80% red; (4) 40% blue/60% red. A spectroradiometer (model SPEC-UV/PAR; Apogee Instruments, Logan, UT) was used to adjust and maintain a light intensity of 250 ± 10 μmols/m^2/sec at the center of each LED panel and the fluorescent/incandescent light treatment at canopy height. The fluorescent/incandescent light treatment was composed of cool-white fluorescent bulbs (160 W) and incandescent bulbs (60 W) and was measured as 15.3% blue (400–500 nm) and 26.4% red (600–700 nm) of total irradiance. The total irradiance of 250 μmols/m^2/sec resulted in a total energy output of 52.3, 49.4, 51.3, and 55.1 W/m^2 for the light treatment of fluorescent/incandescent, 10% blue/90% red LEDs, 20% blue/80% red LEDs, and 40% blue/60% red LEDs, respectively. Treatments provided a red/blue light ratio of 1.7 for fluorescent/incandescent, 9 for 10% blue/90% red, 4 for 20% blue/80% red, and 1.5 for 40% blue/60% red light treatments. Kale plants were harvested from each container at 30 days after seeding from all treatments. Plants were weighed for biomass accumulation and stored at −80 °C prior to tissue analyses.

2.2. Chinese Kale Tissue Mineral Element Analysis

Digestion and mineral nutrient analysis procedures followed those for organically based matrices [14] utilizing a microwave digestion system (ETHOS series; Milestone, Shelton, CT, USA) and an Agilent 7500ce ICP-MS system (Agilent Technologies, Santa Clara, CA, USA).

2.3. Statistical Analyses

The experimental design was a randomized complete block in a two (fertility treatment) × four (light treatment) factorial arrangement. The study was repeated three times. Data were analyzed using the PROC GLM procedure of SAS (version 9.4; SAS Institute, Cary, NC, USA). The mean differences between light and fertility treatments were determined by the least significant difference ($LSD_{\alpha = 0.05}$).

3. Results

The acquisition of mineral nutrients in Chinese kale shoot tissue demonstrated a significant interaction when plants were grown under four light quality treatments within two fertility regimes. The micronutrients Ca, K, Mg, P, and S (Table 1) were all affected by the interaction and, in general, had the highest recorded concentrations in shoot tissue under the ½ strength fertilizer paired with the 20% blue/80% red LED light treatment. Concentrations differed significantly from the ½ strength fertilizer paired with the fluorescent/incandescent light treatment for all except Cu. Interestingly, kale plants grown under the ¼ strength fertilizer paired with the 10% blue/90% red LED light treatments were similar. For example, there was a less than 10% difference between ½ strength fertilizer paired with the 20% blue/80% red LED and the ¼ strength fertility treatment combination for Ca, Mg, P, and S (Table 1).

Conversely, the combination of fluorescent/incandescent light treatments with ¼ strength fertilizer were among the lowest mineral nutrients in kale shoot tissue. For example, K concentrations for the fluorescent/incandescent light treatment combined with the ¼ strength fertilizer treatment were 68.1% lower, while K concentrations for the fluorescent/incandescent light treatment combined with the ½ strength fertilizer treatment were 50.3% lower than the highest value (41.74 mg/g dry mass) recorded for the 20% blue/80% red LED and ½ strength fertility treatments (Table 1). The micronutrients of Mn and Mo also had significant interactions between light and fertility treatments (Table 1). In general,

there were significant increases in Mn and Mo when comparing LED lights and ½ strength fertility treatments and LED lights and ¼ strength fertility and fluorescent/incandescent light combined with fertility. The lowest concentrations in kale shoot Mn and Mo occurred under fluorescent/incandescent light combined with the ¼ strength fertilizer treatment (Table 1). There were 42.4% and 57.8% decreases in the Mo and Mn concentrations, respectively, when comparing the two treatment combinations (Table 1). However, there were no significant changes from the LED lights, and ½ strength fertility treatments and the ¼ strength fertility paired with the 10% blue/90% red LED light treatments (Table 1). Consequently, there were no significant changes in B and Cu in kale shoot tissue treated with different light and fertility treatments (Table 1).

There were limited interactions between light and fertility treatments when determining the mineral nutrient concentrations in the root tissue. For instance, there were only significant interactions for Mo and K that exhibited comparable trends with differences between LED lights and ½ strength fertility treatments and LED lights and ¼ strength fertility and fluorescent/incandescent light combined with fertility (Table 2). The combination of these treatments demonstrated a 42.7% and a 75.0% difference between concentration in the root tissue for Mo and K, respectively. On the other hand, Mg concentrations in kale root tissue demonstrate opposing results that indicated increases under LED lights combined with ¼ strength fertility and fluorescent/incandescent light combined with fertility (Table 2). For instance, concentrations of Mg were similar under the fluorescent/incandescent lights with either fertility treatment and LED lights combined with ¼ strength fertilizer. The smallest amount of Mg in kale root tissue occurred in the 40% blue/60% red LED light combined with ½ strength fertilizer (Table 2).

Light quality had a significant effect on kale shoot Fe and Zn concentrations (Table 1). In all instances, kale plants grown under LED light accumulated higher concentrations of Fe and Zn compared to the fluorescent/incandescent light treatments. The Fe concentrations were greatest in the 40% blue/60% red LED light treatments and increased by 34.9% over the fluorescent/incandescent light treatments (Table 1). The Zn concentrations were greatest under the 10% blue/90% red LED light ratio and increased by 42.1% compared to the fluorescent/incandescent light treatments (Table 1). Conversely, kale plant root concentrations of S, B, and Zn were significantly increased under the 10% blue/90% red LED light ratio treatment (Table 2). Kale plants demonstrated a superior accumulation of S, B, and Zn in the root tissue under the 10% blue/90% red LED light ratio with increases of 34.0%, 39.3%, and 55.1%, respectively, compared to the fluorescent/incandescent light treatments (Table 2).

Fertility treatments of ¼ and ½ strength fertilizer significantly impacted the concentrations of P, Mn, Fe, and Zn in kale root tissue (Table 2). In all instances, ½ strength fertilizer increased the amount of these minerals in the root tissue compared to the ¼ strength fertilizer. The root tissue P, Mn, Fe, and Zn concentrations increased by 16.0%, 51.4%, 40.4%, and 20.5%, respectively (Table 2).

Correlation coefficients were calculated to demonstrate the relationship between kale shoot (Table 1) and root (Table 2) biomass and mineral nutrient concentrations. The results indicated that there were significant negative correlations between kale shoot biomass and Ca, P, K, Mg, S, Fe, Mo, and Zn. There were significant positive correlations between kale root biomass and Ca, Mg, and Cu and negative correlations between root biomass and K, S, B, Mn, Mo, and Zn.

Table 1. The effects of four light quality and two fertility treatments on shoot tissue mineral element concentrations for "Green Lance" Chinese kale (*Brassica oleracea* var *alboglabra*) grown in controlled environments [a].

	Ca	K	Mg	P	S	B	Cu	Fe	Mn	Mo	Zn
Light source [b]	mg/g dry mass [c]							μg/g dry mass [c]			
	¼ Strength fertility [d]										
Fluorescent/Incandescent	15.01 c	13.32 e	2.70 e	4.03 d	4.56 d	53.11 bc	2.56 a	33.03 c	57.74 b	1.29 d	17.70 b
10% blue/90% red LED	22.46 a	34.36 bc	4.04 ab	6.73 abc	9.48 a	51.89 bc	3.22 a	51.39 a	110.78 a	2.36 a	31.61 a
20% blue/80% red LED	18.79 b	23.28 d	3.37 cd	5.92 c	6.59 c	51.93 bc	2.93 a	42.51 abc	71.50 b	1.68 cd	28.41 a
40% blue/60% red LED	20.87 ab	30.12 c	3.95 ab	7.03 ab	7.92 b	56.22 ab	3.36 a	50.29 a	76.65 b	2.07 abc	26.95 a
	½ Strength fertility [d]										
Fluorescent/Incandescent	15.05 c	20.72 d	2.90 de	4.43 d	5.62 cd	51.27 bc	2.93 a	33.56 bc	74.61 b	1.56 cd	18.86 b
10% blue/90% red LED	18.84 b	36.80 ab	3.60 bc	6.43 bc	8.70 ab	50.31 c	3.34 a	46.50 ab	117.94 a	1.78 bcd	31.52 a
20% blue/80% red LED	22.78 a	41.74 a	4.45 a	7.43 a	9.12 ab	58.73 a	3.08 a	54.85 a	136.66 a	2.24 ab	30.20 a
40% blue/60% red LED	22.03 a	39.01 ab	4.19 a	6.89 ab	9.00 ab	53.54 abc	3.11 a	51.98 a	119.77 a	1.97 abc	32.17 a
$SE_{\alpha = 0.05}$ [e]	1.17	2.42	0.26	0.50	0.48	2.32	0.32	5.53	10.69	0.19	2.28
Correlation coefficients [f]	−0.47 **	−0.50 **	−0.40 **	−0.39 **	−0.64 ***	0.01 ns	−0.11 ns	−0.34 ns	−0.26 *	−0.37 **	−0.59 ***
Source of variation [g]											
Light	***	***	***	***	***	ns	ns	**	***	**	***
Fertility	ns	***	ns	ns	**	ns	ns	ns	***	ns	ns
Light x fertility	**	**	**	*	**	ns	ns	ns	*	*	ns

[a] Mean values represent six total plants per treatment for two replications of each of three experimental repeats. Kale plants were harvested 30 days after seeding from all treatments. [b] All light treatments at an intensity of 250 ± 10 μmol/m^2/sec; percentages indicate contributions to total light intensity (see text for light treatment details). [c] Means followed by the same letter are not statistically different, $\alpha = 0.05$. [d] ¼ and ½ strength fertility describe concentrations based on Hoagland's #2 nutrient solution (see text for nutrient concentration details). [e] Standard error of the mean = SE. [f] Correlation coefficients between shoot dry mass (DM) and mineral nutrient concentration with significance as: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; ns, not significant. [g] Individual effects and interactions are given according to ANOVA tests, with significance as: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; ns, not significant.

Table 2. The effects of four light quality and two fertility treatments on root tissue mineral element concentrations for "Green Lance" Chinese kale (*Brassica oleracea* var *alboglabra*) grown in controlled environments [a].

	Ca	K	Mg	P	S	B	Cu	Fe	Mn	Mo	Zn
Light source [b]	mg/g dry mass [c]						μg/g dry mass [c]				
	¼ Strength fertility [d]										
Fluorescent/Incandescent	4.62 a	10.86 c	5.01 abc	3.85 b	5.30 b	41.67 b	15.77 a	101.23 bc	202.24 b	1.10 d	32.52 d
10% blue/90% red LED	4.75 a	30.31 ab	4.59 bc	5.78 a	11.02 a	70.61 a	18.50 a	93.24 c	487.78 ab	2.05 a	70.43 ab
20% blue/80% red LED	5.00 a	18.58 bc	5.37 ab	5.18 ab	6.14 b	39.06 b	17.49 a	75.94 c	274.91 b	1.36 cd	42.28 cd
40% blue/60% red LED	5.16 a	16.11 c	6.37 a	5.84 a	5.32 b	37.29 b	13.06 a	86.52 c	290.36 b	1.55 abcd	35.86 d
	½ Strength fertility [d]										
Fluorescent/Incandescent	4.94 a	13.73 c	5.41 ab	6.67 a	6.08 b	32.96 b	18.08 a	152.69 a	483.31 ab	1.39 cd	37.74 d
10% blue/90% red LED	3.79 a	37.80 a	4.44 d	6.01 a	9.24 ab	52.10 ab	14.71 a	150.84 a	704.97 a	1.49 bcd	77.23 a
20% blue/80% red LED	4.72 a	40.06 a	3.70 cd	6.53 a	8.18 ab	45.68 b	13.40 a	159.90 a	719.74 a	1.92 ab	50.12 bcd
40% blue/60% red LED	4.37 a	43.46 a	3.43 cd	6.37 a	8.58 ab	47.01 b	13.25 a	135.00 ab	677.21 a	1.77 abc	62.79 abc
$SE_{\alpha = 0.05}$ [e]	0.89	4.34	0.86	0.68	1.44	10.47	3.10	24.10	104.00	0.22	8.98
Correlation coefficients [f]	0.33 *	−0.47 **	0.50 **	−0.22 ns	−0.58 ***	−0.46 **	0.30 *	0.12 ns	−0.43 **	−0.35 *	−0.53 **
Source of variation [g]											
Light	ns	***	*	ns	*	*	ns	ns	ns	*	**
Fertility	ns	***	***	*	ns	ns	ns	***	***	ns	*
Light x fertility	ns	*	*	ns	ns	ns	ns	ns	ns	*	ns

[a] Mean values represent six total plants per treatment for two replications of each of three experimental repeats. Kale plants were harvested 30 days after seeding from all treatments. [b] All light treatments at an intensity of 250 ± 10 μmol/m^2/sec; percentages indicate contributions to total light intensity (see text for light treatment details). [c] Means followed by the same letter are not statistically different, $\alpha = 0.05$. [d] ¼ and ½ strength fertility describe concentrations based on Hoagland's #2 nutrient solution (see text for nutrient concentration details). [e] Standard error of the mean = SE. [f] Correlation coefficients between root dry mass (DM) and mineral nutrient concentration with significance as: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; ns, not significant. [g] Individual effects and interactions are given according to ANOVA tests, with significance as: * $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$; ns, not significant.

4. Discussion

The responses of kale biomass from the current study have been published previously [15]. Kale shoot fresh mass (FM) was influenced by light treatment, fertility treatment, and their interaction. Kale shoot tissue FM under ¼ strength fertility was 17.30, 9.24, 11.03, and 9.11 g per plant for the light quality treatments of fluorescent/incandescent light, 10% blue/90% red, 20% blue/80% red, and 40% blue/60% red, respectively. Kale shoot tissue FM under ½ strength fertility was 25.74, 9.27, 13.92, and 11.63 g per plant for the light quality treatments of fluorescent/incandescent light, 10% blue/90% red, 20% blue/80% red, and 40% blue/60% red, respectively. Kale shoot dry mass (DM) was influenced by light treatment, fertility treatment, and their interaction. Kale shoot tissue DM under ¼ strength fertility was 1.75, 1.00, 1.51, and 1.14 g per plant for the light quality treatments of fluorescent/incandescent light, 10% blue/90% red, 20% blue/80% red, and 40% blue/60% red, respectively. Kale shoot tissue DM under ½ strength fertility was 2.76, 0.92, 1.46, and 1.22 g per plant for the light quality treatments of fluorescent/incandescent light, 10% blue/90% red, 20% blue/80% red, and 40% blue/60% red, respectively [15].

Previous LED research on leafy greens has focused on growth, morphological changes, yield, and phytonutrient concentrations. For example, Chen et al. indicated that there were significant differences in plant height, width, FM, DM, and leaf length and leaf width in lettuce grown under red and blue LED light at different daily light integrals [16]. In another study, hypocotyl length, leaf area, FM, and DM were significantly affected by LED photosynthetic photon flux density (PPFD) in *Brassica* microgreens [17]. Previous research has indicated that the addition of blue LED light increased the production of phenolic acids in basil (*Ocimum basilicum*) and flavonoids in arugula (*Eruca vesicaria*) [18]. Kopsell et al. demonstrated that interactions of light quality, comparing fluorescent/incandescent and LED lights, and fertility significantly increased Chinese kale shoot biomass and pigment concentrations [15]. Yan et al. demonstrated similar results comparing fluorescent/incandescent and LED lights with biomass accumulation but also discovered significant differences in vitamin C and soluble protein content in lettuce (*Lactuca sativa*) [19].

Limited research exists on how different LED light ratios affect mineral nutrient concentrations and accumulation. Previous research on LEDs and mineral nutrients has focused on the reduction of nitrate in the leaf and shoot tissues of hydroponically grown leafy greens since the accumulation and concentrations are elevated in these growing systems. For example, a reduction of nitrate concentrations in lettuce leaf tissue was observed when plants were treated with red LED light [20,21]. Previous research also indicated that green LED light reduces nitrate concentrations in hydroponically grown lettuce [22]. However, there is a lack of knowledge of how LED light ratios, coupled with differing concentrations of a hydroponic nutrient solution, affect mineral nutrient concentrations and accumulation in shoot and root tissues.

Even though there is limited research information on different nutrient solution concentrations and LED lights, other studies have demonstrated how differing LED light ratios affect the uptake of mineral nutrients in leaf tissues. For example, Gerovac et al. indicated that LED light quality, the ratio of red, green, far-red, and blue light, and LED light intensity had significant effects on macronutrient concentrations in *Brassica* microgreens [23]. Previous research has also indicated that sprouting broccoli shoot tissue macronutrients were significantly affected when grown under red and blue LED or five-day preharvest blue LED light treatments [11]. Metallo et al. found similar results with LED and white light and duration treatments for K concentrations in kale plants [24]. The data indicated that 95% red/5% blue at the 37-day treatments increased K concentrations to 4.87% compared to 3.61% in white light treatment. In the current study, the interaction of light and fertility had a profound effect on the concentrations of macronutrients in kale shoot tissue. Another study demonstrated that LED light treatment affected mineral nutrients such as Ca, K, Mg, P, and S in microgreen production [10]. Comparable results were discovered in the current study that indicated increases in mineral nutrients under LED lights compared to fluorescent/incandescent lights. Thus, LED light quality and an adequate fertility program can lead to a significant impact on increasing

macronutrient uptake and concentrations in plant tissues, increasing the quality and nutritional content of edible kale tissue. In the current study, the results also indicate that the biomass dilution effect was a factor when increasing the nutrient solution concentrations under LED light quality conditions versus fluorescent/incandescent light, with adequate light intensities. The evidence indicated a negative relationship when comparing the shoot biomass data [15] to the mineral nutrient concentrations in the current study. The negative relationship demonstrated that as mineral nutrient concentration decreased in the shoot tissue, the biomass of the kale plant increased, indicating a biomass dilution affect in the kale shoot tissue. However, in some cases root biomass was positively correlated with mineral nutrient concentrations in the root tissue. In this and previous studies, the light intensities for growing leafy greens such as kale have been approximately 250 to 350 $\mu mols \cdot m^2 \cdot sec^{-1}$, indicating that within this light intensity range, plants given the correct LED light quality and increased fertility can have elevated concentrations of mineral nutrients.

There were fewer effects of the interaction of light and fertility on micronutrient concentrations in kale shoot tissue. Previous research indicated that the interaction of light quality and intensity decreased concentrations of B, Fe, and Zn in kohlrabi (*B. oleracea* var *gongylodes*), mizuna (*B. rapa* var *japonica*), and mustard (*B. juncea* (L.) Czern. "Garnet Giant") [23]. These results indicated that decreases in micronutrient concentrations may have been caused by increases in biomass under increased light intensity and pinpointed light quality giving a biomass dilution effect under these conditions.

5. Conclusions

LED light research on leafy greens has indicated that light ratios can be manipulated to impact mineral nutrient uptake and stimulate secondary metabolic pathways associated with nutritional quality factors. Several previous studies within our collaborative research efforts demonstrated the ability to increase secondary metabolic pathways and mineral nutrient uptake associated with nutritional quality factors [10,11,15,24]. However, the current research study was the first to examine how novel LED light ratios and differing fertilizer regimes affect mineral nutrient concentrations in *Brassica* root and shoot tissues. By manipulating light ratios and mineral nutrient concentrations, it is possible that plants can be manipulated with novel LED light ratios coupled with lower mineral nutrients for a more sustainable approach to plant growth.

Author Contributions: Conceptualization, D.A.K., C.E.S., and R.C.M.; Methodology, D.A.K. and C.E.S.; Validation, T.C.B., D.A.K., C.E.S., and R.C.M.; Formal analysis, T.C.B., D.A.K., and C.E.S.; Investigation, T.C.B., D.A.K., C.E.S., and R.C.M.; Resources, D.A.K., C.E.S., and R.C.M.; Data curation, T.C.B. and D.A.K.; Writing—original draft preparation, T.C.B. and D.A.K.; Writing—review and editing, T.C.B., D.A.K., and C.E.S.; Visualization, D.A.K., C.E.S., and R.C.M.; Supervision, D.A.K. and C.E.S.; Project administration, D.A.K., C.E.S., and R.C.M.; Funding acquisition, D.A.K., C.E.S., and R.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded in part by USDA-NIFA-SBIR Project 2012-33610-19526. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the view of the National Institute of Food and Agriculture (NIFA), the U.S. Department of Agriculture (USDA), or Orbital Technologies Corporation.

Conflicts of Interest: The authors declare no competing financial interests. The research was conducted at the University of Tennessee. Data analysis and the writing of the manuscript were conducted at Mississippi State University and the University of Florida.

References

1. Engels, C.; Kirkby, E.; White, P. Mineral nutrition, yield and source-sink relationships. In *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Marschner, P., Ed.; Academic Press: London, UK, 2012.
2. Römheld, V. Diagnosis of deficiency and toxicity of nutrients. In *Marschner's Mineral Nutrition of Higher Plants*, 3rd ed.; Marschner, P., Ed.; Academic Press: London, UK, 2012.

3. McCree, K.J. Test of current definitions of photosynthetically active radiation against leaf photosynthesis data. *Agric. Meteorol.* **1972**, *10*, 443–453. [CrossRef]
4. Zuber, H. Structure of light-harvesting antenna complexes of photosynthetic bacteria, cyanobacteria and red algae. *Trends Biochem. Sci.* **1986**, *11*, 414–419. [CrossRef]
5. Demmig-Adams, B.; Adams, W.W., III. The role of xanthophyll cycle carotenoids in the protection of photosynthesis. *Trends Plant Sci.* **1996**, *1*, 21–26. [CrossRef]
6. Mills, H.A.; Jones, J.B., Jr. Factors affecting plant composition. In *Plant Analysis Handbook II*; MicroMacro Publishing, Inc.: Athens, GA, USA, 1996.
7. Glass, A.D.M. Environmental influences on ion absorption. In *Plant Nutrition: An Introduction to Current Concepts*; Jones and Bartlett Publishers, Inc.: Boston, MA, USA, 1989.
8. Barber, S.A. Potassium. In *Soil Nutrient Bioavailability: A Mechanistic Approach*; Wiley & Sons, Inc.: New York, NY, USA, 1995.
9. Zhao, X.; Wang, Y.L.; Qiao, X.R.; Wang, J.; Wang, L.D.; Xu, C.S.; Zhang, X. Phototropins function in high-intensity blue light induced hypocotyl phototropism in Arabidopsis by altering cytosolic calcium. *Plant Physiol.* **2013**, *162*, 1539–1551. [CrossRef] [PubMed]
10. Kopsell, D.A.; Sams, C.E.; Barickman, T.C.; Morrow, R.C. Sprouting broccoli accumulate higher concentrations of nutritionally important metabolites under narrow band light-emitting diode lighting. *J. Am. Soc. Hortic. Sci.* **2014**, *139*, 469–477. [CrossRef]
11. Kopsell, D.A.; Sams, C.E. Increases in shoot tissue pigments, glucosinolates, and mineral elements in sprouting broccoli after exposure to short-duration blue light from light-emitting diodes. *J. Am. Soc. Hortic. Sci.* **2013**, *138*, 31–37. [CrossRef]
12. Baligar, V.C.; Fageria, N.K.; Paiva, A.Q.; Silveira, A.; Pomella, A.W.V.; Machado, R.C.R. Light intensity effects on growth and micronutrient uptake by tropical legume cover crops. *J. Plant Nutr.* **2006**, *29*, 1959–1974. [CrossRef]
13. Hoagland, D.R.; Arnon, D.I. The water culture method for growing plants without soil. *Calif. Agric. Exp. Stn.* **1950**, *347*, 1–32.
14. Barickman, T.C.; Kopsell, D.A.; Sams, C.E. Selenium influences glucosinolate and isothiocyanates and increases sulfur uptake in Arabidopsis thaliana and rapid-cycling *Brassica oleracea*. *J. Agri. Food Chem.* **2013**, *61*, 202–209. [CrossRef] [PubMed]
15. Kopsell, D.A.; Sams, C.E.; Morrow, R.C. Interaction of light quality and fertility on biomass, shoot pigmentation and xanthophyll cycle flux in Chinese kale. *J. Sci. Food Agric.* **2017**, *97*, 911–917. [CrossRef] [PubMed]
16. Chen, X.; Yang, Q.; Song, W.; Want, L.; Gou, W.; Xue, X. Growth and nutritional properties of lettuce affected by different alternating intervals of red and blue LED irradiation. *Sci. Hortic.* **2013**, *223*, 44–52. [CrossRef]
17. Jones-Baumgardt, C.; Llewellyn, D.; Ying, Q.; Zheng, Y. Intensity of sole-source light-emitting diodes affect growth, yield, and quality of *Brassicaceae* microgreens. *HortScience* **2019**, *54*, 1168–1174. [CrossRef]
18. Taulavuori, K.; Pyysalo, A.; Taulavuori, E.; Julkunen-Tiitto, R. Response of phenolic acid and flavonoid synthesis to blue and blue-violet light depends on plant species. *Environ. Exp. Bot.* **2018**, *150*, 183–187. [CrossRef]
19. Yan, Z.; He, D.; Niu, G.; Zhai, H. Evaluation of growth and quality of hydroponic lettuce at harvest as affected by the light intensity, photoperiod and light quality at seedling stage. *Sci. Hortic.* **2019**, *248*, 138–144. [CrossRef]
20. Samuloiene, G.; Urbonaviciute, A.; Duchovskis, P.; Bliznikas, Z.; Vitta, P.; Zukauskas, A. Decrease in nitrate concentrations in leafy vegetables under a solid-state illuminator. *HortScience* **2009**, *44*, 1857–1860. [CrossRef]
21. Liu, H.; Fu, Y.; Yu, J.; Liu, H. Accumulation and primary metabolism of nitrate in lettuce (*Lactuca sativa* L. var. Youmaicai) grown under three different light sources. *Comm. Soil Sci. Plant Anal.* **2016**, *47*, 1994–2002. [CrossRef]
22. Bian, Z.; Cheng, R.; Wang, Y.; Yang, Q.; Lu, C. Effect of green light on nitrate reduction and edible quality of hydroponically grown lettuce (*Lactuca sativa* L.) under short-term continuous light from red and blue light-emitting diodes. *Environ. Exp. Bot.* **2018**, *153*, 63–71. [CrossRef]

23. Gerovac, J.R.; Craver, J.K.; Boldt, J.K.; Lopez, R.C. Light intensity and quality from sole-source light-emitting diodes impact growth, morphology, and nutrient content of Brassica microgreens. *HortScience* **2016**, *51*, 497–503. [CrossRef]
24. Metallo, R.M.; Kopsell, D.A.; Sams, C.E.; Bumgarner, N.R. Influence of blue/red vs. white LED light treatments on biomass, shoot morphology, and quality parameters of hydroponically grown kale. *Sci. Hortic.* **2018**, *235*, 189–197. [CrossRef]