Elevated Levels of Potassium in Greenhouse-grown Red Romaine Lettuce Impacts Mineral Nutrient and Soluble Sugar Concentrations

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Abstract. Lettuce is one of the major crops of the United States and can provide a large portion of income for small to medium size growers. Growing lettuce in adverse environmental conditions can have negative effects on quality. Elevated levels of potassium (K) have been shown to positively influence quality in various fruits and vegetables, such as tomato, pepper, and strawberry. However, research is lacking on the effects of elevated levels of K on leafy vegetables such as lettuce. Therefore, seeds of ‘Cimmaron’ lettuce were sown into a soilless medium and grown in greenhouse conditions at 25/20 °C (day/night). At 27 days after seeding, the plantlets were transferred to 3.8-L plastic nursery pots. Plants were grown under increasing K treatments of 98 (control), 185 (2×), 370 (3×), and 740 (8×) kg·ha⁻¹. Plants were harvested 56 days after seeding. Application of elevated levels of K fertilizer treatments in red romaine lettuce had a positive quadratic effect on plant height increasing 7.0% from the control. Fresh weight (FW) increased 13.0% from the control and dry weight (DW) increased 15.5%. There was linear increase of 30.0% in sucrose concentrations in lettuce leaf tissue. In addition, the increase in K treatments caused an increase of 43.3% in K concentrations in the leaf tissue. In other nutrients, such as Calcium (Ca), Magnesium (Mg), and Sulfur (S), there was a decrease in the leaf tissue of 61%, 52%, and 46% when compared with the control treatment, respectively. The results of the current study suggest that increasing K fertilizer to 185 kg·ha⁻¹ has the best results for plant height, FW and DW, and mineral nutrient concentrations. This study may initiate research that could examine the effects of increasing K fertilizer levels in lettuce or other leafy green vegetables on antioxidant levels and postharvest storability.

Open field and greenhouse production of lettuce (*Lactuca sativa*) in southern United States occurs predominately in the fall and winter seasons due to lower temperatures and shorter days. In most southern states, lettuce provides a large amount of income. Romaine type lettuce is the main lettuce grown by small to medium producers. Depending on plant spacing, the average yields of romaine lettuce can be around 30,000 kg·ha⁻¹ (Mossler and Dunn, 2005). Romaine type lettuce is a preferred leafy green grown in these operations because of consumer preferences due to its higher nutritional value compared with head type lettuce. In adverse environmental

conditions, such as high temperatures and inadequate fertilization, lettuce can decrease in quality by having long internodes, becoming bitter in taste, and having increased incidences of tipburn (Bres and Weston, 1992; Eskins et al., 1995). For example, lettuce grown under limited Ca had a chlorotic appearance and reduced growth. Lack of boron (B) also caused lettuce to have wrinkled leaf tissue, lose apical dominance, and exhibit limited plant growth (Petrizzini et al., 2014). In addition, Luo et al. (2012) found that increasing K in lettuce plants elevated soluble sugar, starch, and leaf K concentrations when grown under different root-zone temperatures. On the other hand, effects of different temperature regimes resulted in differences in chlorophyll and anthocyanin content in greenhouse-grown red leaf lettuce (Kleinhenz et al., 2003). Thus, growing lettuce under adverse environmental conditions can have an unfavorable effect on growth, yield, and quality.

Potassium is vital to plant growth, yield, and quality even though it is not a constituent of any functional molecules or plant

structures (Marschner, 2012). In addition, it helps to regulate stomatal conductance and photosynthesis. Potassium is also involved in photophosphorylation, transport of photo-assimilates from source to sink tissues via the phloem, enzyme activation, turgor maintenance, and stress tolerance (Marschner, 2012). However, K may be best known to positively influence many qualities of fruits and vegetables. Previous research has demonstrated that K fertilizer applied to the soil enhanced color, increased fruit tissue firmness, and elevated soluble sugar concentrations in apple (*Malus ×domestica*) fruit tissue (Nava et al., 2008). However, contrasting results have been indicated in previous research. For instance, Fallovo et al. (2009a) examined how different nutrition solution concentrations affected lettuce yield and quality. The results indicated that the effect of the growing season on yield and quality was more prominent than that of the nutrient solution composition. Thus, results from K research studies are variable in different plant species for growth, yield, and quality.

Research has indicated that supplemental K nutrition has been associated with increased fruit size and higher soluble solid and ascorbic acid concentrations (Lester et al., 2005). Studies have shown that supplemental K increases yield and carotenoids in vegetables such as tomato (*Solanum lycopersicum*) (Fanasca et al., 2006; Taber et al., 2008) and pepper (*Capsicum annuum*) (Anathi et al., 2004), and size, color, firmness, and sugar content in tree fruits, such as apple (Wojcik, 2005) and citrus (Dutta et al., 2003; Srivastava et al., 2001). Some of the most successful supplemental K research has been conducted on muskmelon (*Cucumis melo*). For example, Lester et al. (2005, 2006) found that supplemental applications of K increased fruit firmness, vitamins, sugars, and yield. In addition, Jifon and Lester (2009) examined different forms of K fertilization to improve quality of field-grown muskmelons. They found that late season foliar K applications increased tissue K concentration, fruit sugars, and bioactive compounds such as ascorbic acid and β-carotene.

Research associated with adequate and elevated levels of K on lettuce yield and quality is limited and inconclusive. Some studies found that K in nutrient solution did not affect lettuce yield and quality. For example, Fallovo et al. (2009b) investigated the effects of macro-anion and cation ratios in hydroponic lettuce in two different seasons. The results indicated that the change in season from spring to summer and increasing the fertilizer concentrations increase plant growth and yield. Soundy et al. (2001) demonstrated that increasing levels of K in the nutrient solution from 15 to 60 mg·L⁻¹ increased fresh and dry root weight at 28 d after transplant. Other studies found inconclusive results on the effects of K applications. Bres and Weston (1992) demonstrated that increasing pH levels at two different K concentrations did not affect tipburn

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incidence in hydroponically grown lettuce. In addition, Hoque et al. (2010) applied different combinations of nitrogen (N), phosphorus (P), and K but concluded that K did not affect quality compared with N and P. The limited research for K treatment effects on lettuce yield and quality demonstrate some positive results; however, more research is needed to explain variable results. The purpose of this study was to determine the effect of adequate and elevated levels of K on greenhouse-grown lettuce plant height, biomass accumulation, mineral nutrient uptake, and soluble sugar concentrations.

Materials and Methods

Plant material, growing conditions, and treatments. Seeds of 'Cimmaron' lettuce (Harris Seeds, Rochester, NY) were sown into Pro-Mix BX soilless medium (Premier Tech Horticulture, Québec, Canada) and germinated in greenhouse conditions at 25/20 °C (day/night). At 27 d after seeding, the plantlets were transferred to 3.8-L plastic nursery pots filled with Pro-Mix BX soilless medium. Plants were fertilized with 28 g (Osmocote; Scotts Miracle-Gro, Marysville, OH) of 15N–3.9P–9.9K. The N, P, and K were then calculated on a kg·ha⁻¹ basis. Elemental concentrations of nutrients applied to the plants were (kg·ha⁻¹): nitrogen (N; 139) and phosphorus (P; 36). Plants were grown under increasing K treatments of 98 (control), 185 (2×), 370 (3×), and 740 (8×) kg·ha⁻¹. Elevated K treatments were applied as potash (0N–0P–49.8K). The experiment was carried out on 16 Sept. 2014 and on 2 Mar. 2015. Natural photoperiod and intensity of sunlight averaged 350 μmol·m⁻²·s⁻¹ over the entire photoperiod. Light intensity readings were taken at 1.22 m off the ground. Experimental design was a randomized complete block with four K treatments, four replications, and five individual pots representing an experimental unit with one lettuce plant per pot. Treatments of elevated K were side-dressed at three different times during the experiment at 1/3 the amount of the full treatment total. Plants were harvested at 54 d after seeding. Subsequently, lettuce plants from each treatment were separated by replication and weighed for biomass. At least three leaves from each experimental unit were subsampled, frozen, and prepared for elemental nutrient and soluble sugars. Samples were stored at –20 °C before analysis.

Mineral composition. Nutrient analysis was conducted according to Barickman et al. (2013) with slight modifications. In brief, leaves were collected and dried for 48 h in a forced air oven (model large; Fisher Scientific, Atlanta, GA) at 65 °C. Dried samples were ground to homogeneity using liquid nitrogen, and 0.5-g subsamples were combined with 10 mL of 70% HNO₃ and digested in a microwave digestion unit (Model: Ethos; Milestone Inc., Shelton, CT). Nutrient analysis was conducted using an inductively coupled plasma mass spectrometer (ICP-MS; Agilent

Technologies, Inc., Wilmington, DE). The ICP-MS system was equipped with an octapole collision/reaction cell, Agilent 7500 ICP-MS ChemStation software, a Micromist nebulizer, a water-cooled quartz spray chamber, and a CETAC (ASX-510, CETAC Inc., Omaha, NE) auto-sampler. The instrument was optimized daily in terms of sensitivity (lithium: Li, yttrium: Y, thallium: Tl), level of oxide, and doubly charged ion using tuning solution containing 10 μg·L⁻¹ of Li, Y, Tl, cerium (Ce), and cobalt (Co) in a 2% HNO₃/0.5% HCl (v/v) matrix. Tissue nutrient concentrations are expressed on a DW basis.

Soluble sugar analysis. Soluble sugar analysis was conducted according to Barickman et al. (In press). In brief, lettuce leaf samples were ground in a bullet grinder for homogenous subsamples. A 2.0-g subsample was extracted in a 15-mL test tube by adding 2 mL of reverse osmosis (RO) water, vortexing, and shaking for 15 min at 200 rpm. Samples were then centrifuged at 4000 rpm for 10 min, and 1.0 mL of the supernatant was transferred into a new 15-mL test tube. After the transfer, 1.4 mL of acetonitrile was added, and tubes were mixed by inversion and kept at room temperature for 30 min. Samples were then centrifuged at 4000 rpm for 10 min, and 1.0 mL of the supernatant was transferred into a new 15-mL tube and placed into a dry bath until complete evaporation. Once dried, samples were dissolved in 0.5 mL of 75% acetonitrile and 25% RO water. Samples were then put through a 0.2-μm syringe filter and collected in a 2 mL-high performance liquid chromatography (HPLC) vial for analysis. Separation parameters and sugar quantification were carried out with authentic standards using an Agilent 1100 series HPLC with a refractive index detector (Agilent Technologies). Chromatographic separations were achieved using a 250 × 4.6 mm i.d. 5 μm analytical scale NH₂ (amino) carbohydrate C₁₈ reverse-phase column (Agilent Technologies), which allowed for effective separation of chemically similar sugar compounds. The column was equipped with a Zorbax NH₂ 4.6 × 12.5 mm i.d. guard cartridge and holder (Agilent Technologies), and was maintained at 30 °C using a thermostatted column compartment. All separations were achieved isocratically using a binary mobile phase of 75% acetonitrile and 25% RO water (v/v). The flow rate was 1.0 mL·min⁻¹, with a run time of 15 min, followed by a 2-min equilibration before the next injection. Eluted compounds from a 10-μL injection loop were detected in positive detection mode, and data were collected, recorded, and integrated using ChemStation Software (Agilent Technologies). Peak assignment for individual sugars was performed by comparing retention times from the refractive index detector using external standards of fructose and glucose (Sigma-Aldrich, St. Louis, MO).

Statistical analysis. The experimental design was a randomized complete block with four K treatments and four replications. The

two experiments were statistically similar. Therefore, data were pooled and analyzed together for treatment means. The fixed effect for the experiment consisted of the four K treatments, whereas replications were analyzed as random effects. The standard errors were based on the pooled error term from the analysis of variance table. Model-based values were reported rather than unequal standard error from a databased calculation because pooled errors reflect the statistical testing being done. Orthogonal polynomials were used to study changes associated with K treatments by partitioning the sums of squares into components associated with linear and quadratic terms. Diagnostic tests were conducted to insure that treatment variances were statistically equal before pooling.

Results

K influence on plant growth and biomass production of red romaine lettuce. Increasing K treatments significantly influenced lettuce biomass. Fresh weight had a positive quadratic response with increasing levels of K treatments (Fig. 1). Levels of FW were 526.4 g in the control treatment, increasing 11% in 2× K treatments, and then decreasing 26% from the 2× to the 8× K treatments. Correspondingly, DW had a positive quadratic response with increasing K treatment levels (Fig. 2). Levels of DW were 48.5 g in the control treatment, increasing 16% in 2× K treatments, and then decreasing 35% from the 2× to the 8× K treatments. Similarly, plant heights had a positive quadratic response with increasing K treatment levels (Fig. 3). Plant height was 32.4 cm in the control treatment, increasing 7% in 2× K treatments, and then decreasing 5% in the 8× K treatment.

K influence on mineral nutrient concentration in leaf tissue. Increasing levels of K significantly increased K concentrations in the leaf tissue of red romaine lettuce. Levels of K increased linearly by 40% when comparing the control to the 8× treatment. In contrast, there was a decrease in the levels of Na, Mg, S, Ca, B, and Fe in the leaf tissue of red romaine lettuce. With increased rates of K fertilizer treatments, Na decreased linearly by 40% from the control to the 8× K treatment. Levels of Mg decreased 52%, in the 8× K treatment when compared with the control. Similarly, S decreased 46%, Ca decreased 61%, B decreased 33%, and Fe decreased 42% (Table 1). Furthermore, levels of Mn, Cu, and Zn had a positive quadratic response with increasing levels of K treatments. Levels of Mn increased 27% in the 2× K treatments while decreasing 57% in the 8× K treatments. Similarly, levels of Cu were 0.02 mg·g⁻¹ DW in the control treatment, increasing 60% in 2× K treatment while decreasing 60% in the 3× and 8× K treatments. Levels of Zn were 0.07 mg·g⁻¹ DW in the control treatment, increasing 22% in the 2× K treatment while decreasing 11% in 3× K treatment and 33% in 8× K treatment (Table 1). There were no

Fig. 1. The effect of adequate and elevated levels of potassium on fresh weight of greenhouse-grown red romaine lettuce plants harvested 56 d after seeding.

Fig. 2. The effect of adequate and elevated levels of potassium on dry weight of greenhouse-grown red romaine lettuce plants harvested 56 d after seeding.

Fig. 3. The effect of adequate and elevated levels of potassium on plant height of greenhouse-grown red romaine lettuce plants harvested 56 d after seeding.

significant differences in levels of P and Mo in red romaine lettuce leaf tissue (Table 1).

Influence of increasing K treatments on red romaine lettuce soluble sugars. The increasing levels of K significantly increased sucrose concentrations (Fig. 4). Sucrose concentrations increased $\approx 30\%$, from $7.61 \text{ mg}\cdot\text{g}^{-1}$

DW to $10.76 \text{ mg}\cdot\text{g}^{-1}$ DW, when comparing the K control treatment to the $8\times$ K treatment. Fructose had a negative quadratic response to increasing levels of K treatments (Fig. 5). Fructose concentrations were $119.12 \text{ mg}\cdot\text{g}^{-1}$ DW in the control treatment, decreasing to $111.54 \text{ mg}\cdot\text{g}^{-1}$ DW in $2\times$ treatments and

$110.72 \text{ mg}\cdot\text{g}^{-1}$ DW in $3\times$ treatment, and then increasing to $115.52 \text{ mg}\cdot\text{g}^{-1}$ in the $8\times$ treatment. Increasing levels of K did not significantly influence glucose concentrations (Fig. 6). Total sugars had a negative quadratic response to increasing K treatments (Fig. 7). Total sugar concentrations were $151.20 \text{ mg}\cdot\text{g}^{-1}$ DW in the control treatment, decreasing to $140.75 \text{ mg}\cdot\text{g}^{-1}$ DW in $2\times$ treatments and $140.47 \text{ mg}\cdot\text{g}^{-1}$ DW in $3\times$ treatment, and then increasing to $151.20 \text{ mg}\cdot\text{g}^{-1}$ DW in the $8\times$ treatment.

Discussion

The current study examines how adequate and elevated levels of K fertilizer affect red romaine lettuce plant height, biomass, mineral nutrient uptake, and concentrations of soluble sugars. Although elevating levels of K fertilizer was beneficial for plant height and biomass of red romaine lettuce, a saturation point was reached and then there were negative effects at higher levels of K fertilizer applications. This was evident when applying $3\times$ and $8\times$ K treatments. Field application of granular K fertilizers, such as potash, contain high levels of chloride especially at the $3\times$ and $8\times$ treatment levels. These high levels can create salt stress that can reduce growth and development, yields, and other metabolites, such as soluble sugars, in lettuce leaf tissues. For example, previous research on field grown lettuce, cabbage (*Brassica oleracea*), and celery (*Apium graveolens*) also indicated that oversupply of K depresses plant growth and yield (Inthichack et al., 2012). However, these findings are not consistent with other research on lettuce. For instance, Fallovo et al. (2009a, 2009b) demonstrated that changes in nutrient solution with K and other nutrients did not affect lettuce yield and quality. In addition, Soundy et al. (2001) found that elevating K in the nutrient solution for hydroponically grown lettuce did not affect growth rate or shoot and root biomass accumulation. The reason why results do not support previous research may be found in the medium the lettuce plants were grown. The current study treated lettuce plants with elevated levels of K in a soilless medium, while Fallovo et al. (2009a, 2009b) and Soundy et al. (2001) treated the hydroponic solution with different concentrations of K. In a soilless medium, plants are able to take up nutrients as they become available from the soil solution, which depends on buffering capacity, pH, and moisture. In contrast, purified water is normally used for hydroponic solutions and has minimal buffering capacity and constant water supply. This allows the plants to take up nutrients readily from the nutrient solution when the pH is maintained between 5.5 and 6.0.

Excess K supply has an impact on the uptake of other mineral nutrients such as Ca and Mg. In these instances, the cytosol becomes less negative due to the influx of K. This depolarization reduces the driving force for the uptake of other cationic species, which are otherwise taken up by facilitated

Table 1. Elemental nutrient concentrations of greenhouse-grown 'Cimmaron' red romaine lettuce plants at adequate and elevated levels of potassium.

Potassium (kg·ha ⁻¹)	Elemental nutrient concentrations [mg·g ⁻¹ dry weight (DW)] ^{z,y}											
	Na	Mg	P	S	K	Ca	B	Mn	Fe	Cu	Zn	Mo*
98.61	1.45	6.07	4.80	3.27	31.54	10.13	0.03	0.22	0.40	0.02	0.07	0.03
185.17	1.19	6.51	5.40	2.53	48.80	10.65	0.03	0.30	0.55	0.05	0.09	0.04
370.34	0.98	4.59	5.86	2.37	55.68	6.66	0.03	0.22	0.35	0.02	0.08	0.03
740.53	0.87	2.91	4.87	1.75	53.03	3.95	0.02	0.13	0.23	0.02	0.06	0.02
Contrast												
Linear	*	**	NS	**	**	**	**	NS	*	NS	NS	NS
Quadratic	NS	NS	NS	NS	*	NS	*	*	NS	*	***	NS

^zNa = sodium; Mg = magnesium; P = phosphorus; S = sulfur; K = potassium; Ca = calcium; B = boron; Mn = manganese; Fe = iron; Cu = copper; Zn = zinc; Mo = molybdenum.

^yThe standard error of the mean was Na ± 0.16; Mg ± 0.70; P ± 0.50; S ± 0.31; K ± 4.65; Ca ± 1.41; B ± 0.002; Mn ± 0.04; Fe ± 0.08; Cu ± 0.007; Zn ± 0.005; Mo ± 0.01.

*Mo given as µg·g⁻¹ DW.

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, 0.001, respectively.

Fig. 4. Sucrose concentrations of greenhouse-grown red romaine lettuce plants treated with adequate and elevated potassium levels and harvested 56 d after seeding.

Fig. 5. Fructose concentrations of greenhouse-grown red romaine lettuce plants treated with adequate and elevated potassium levels and harvested 56 d after seeding.

diffusion (Marschner, 2012). The current study corresponded to this decree by decreasing Ca and Mg in lettuce leaf tissue with increasing K application rate. Previous research has also demonstrated that growing season and nutrient solution composition affect N, K, and Mg uptake by plants. However, Ca concentrations did not differ with nutrient solution concentrations (Fallovio et al., 2009a, 2009b). These trends were evident

in the current experiment with red romaine lettuce when plants were treated with elevated levels of K, the uptake of B, Mg, S, Ca, and Fe in leaf tissue significantly decreased. Previous research has indicated that K concentrations can range from ≈25 to 54 mg·g⁻¹ DW in the youngest fully developed leaves of lettuce (Bergmann, 1993). This research supports the results of the current study in which K concentration in the youngest

fully developed leaves ranged from ≈31 to 55 mg·g⁻¹ DW.

It is well established that K increases quality of fruits and vegetables by improving yields, color, firmness, and soluble sugars (Lester et al., 2010). Specifically, Li et al. (2008) found that foliar spray treatments improved tomato plant growth and vitamin C, soluble sugars, and organic acids in the fruit. Research also indicated that application of potassium sulfate to the soil improved apple fruit quality, such as color, firmness, and soluble sugars (Attala, 1998; El-Gazzar, 2000). However, expansive research on yield and quality of leafy green vegetables in response to adequate and elevated levels of K fertilizer treatments is needed. Previous research on application of elevated K levels on leafy greens yielded inconclusive results. One study indicated that elevating K increased yield and decreased Mg and Ca in the leaf tissue of lettuce and other vegetables (Inthichack et al., 2012). Additional research has demonstrated that differing levels of K in the nutrient solution of hydroponically grown lettuce did not affect yield, biomass, and quality such as soluble sugars (Fallovio et al., 2009a, 2009b; Soundy et al., 2001). In the current study, even though levels of total sugar in the leaf tissue decreased with increasing levels of K application, there were increases in FW, DW, and plant height at the 2× and 3× K applications. Monosaccharides, such as fructose and glucose, in red romaine lettuce leaf tissue decreased in concentration when levels of K fertilizer treatments increased. These results indicate that lettuce plants treated with elevated levels of K use the monosaccharides to build structural carbohydrates to add more biomass to the plant. Research has demonstrated inverse relationships between tissue concentrations of K and sugars, reducing sugars in particular, and can be observed during the growth of storage tissue.

In carrot (*Daucus carota*), results indicated that an increase in the concentration of reducing sugars is compensated for by a corresponding decrease in the concentration of K and organic acid anions (Steingrover, 1983). These results correspond with the current study in that increasing the K concentrations in red romaine lettuce leaf tissue decreased the concentration of fructose and glucose. Thus, an inverse relationship of the concentrations

Fig. 6. Glucose concentrations of greenhouse-grown red romaine lettuce plants treated with adequate and elevated potassium levels and harvested 56 d after seeding.

Fig. 7. Total soluble sugar concentrations of greenhouse-grown red romaine lettuce plants treated with adequate and elevated potassium levels and harvested 56 d after seeding.

between K and fructose and glucose was present. However, there was a point where adding K to lettuce plants increased the sugars. At the 8× K fertilizer treatment, sugars again increased in lettuce leaf tissue. These results indicate that instead of adding more biomass there was an accumulation of soluble sugars in the leaf tissue, suggesting that there was a stronger source to sink relationship in the lettuce plant tissue.

The translocation of phloem-mobile nutrients, such as K, from shoots to roots together with photosynthetic carbon is a normal feature during ontogenesis (Jeschke and Pate, 1991). Although this translocation may serve specific regulatory functions for any particular mineral nutrient, it might also be the consequence of the mechanism of phloem loading photoassimilates, particularly sucrose, in the source leaves (Komor, 1994). Therefore, increasing the levels of K fertilizer treatments may also increase the levels of sucrose in the leaf tissue. In a previous study, Beringer et al. (2006) demonstrated that elevating K fertilizer concentrations increased sugar beet (*Beta vulgaris*) root DW from 269 to 310 g per plant. Furthermore, the authors were able to increase

sucrose concentrations from 15.0% to 17.7% FW in the storage roots. In red romaine lettuce, increasing the K fertilizer treatments from 98 to 741 kg·ha⁻¹ also increased sucrose concentrations in the leaf tissue. Thus, increasing the K concentrations in lettuce may increase phloem loading of sucrose into the leaf tissue.

In conclusion, the application of elevated levels of K fertilizer treatments in red romaine lettuce has a positive quadratic effect on plant height, FW, and DW, and a linear increase in sucrose concentrations. Applications of elevated levels of K fertilizer treatments can improve red romaine lettuce yields and quality by increasing plant biomass and sucrose concentrations in the leaf tissue. Therefore, treating red romaine lettuce with elevated levels of K fertilizer was beneficial for yield and quality. However, results also indicate that there was a saturation point after which yield and quality declined. In hydroponic lettuce production, mineral nutrients are more available to the plant. In this situation, lowering the mineral nutrient concentrations increased sugar beet (*Beta vulgaris*) root DW from 269 to 310 g per plant. For the best yield and quality of lettuce plants

indicated from this study, K fertilizer treatments should range between 180 and 370 kg·ha⁻¹ for soilless greenhouse and field production.

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