Research Article

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Foliar potassium fertilization improves fruit quality of field-grown muskmelon on calcareous soils in south Texas

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Abstract

BACKGROUND: Among plant nutrients, potassium (K) has the strongest influence on crop quality parameters that determine consumer preference. However, soil and plant factors often limit adequate soil K uptake to satisfy quality requirements during fruit development stages. The objectives of this multiyear field study with muskmelon were to determine if this apparent K deficiency and the associated fruit quality limitations can be alleviated by supplementing soil-derived K with foliar K nutrition, and whether differences exist among potential foliar K salts.

RESULTS: Foliar K treatments increased tissue K concentrations, fruit sugars and bioactive compounds (ascorbic acid and β-carotene) by 19%, 21% and 15%, respectively, even though soil K levels were high, indicating that soil K alone was inadequate to improve these quality traits. All the K salts evaluated increased tissue K and fruit quality traits; however, no clear trends in the relative magnitudes of these enhancements were apparent among K sources, except for KNO_3 which consistently resulted in non-significant effects.

CONCLUSIONS: These results demonstrate that late-season foliar K feeding can improve fruit quality of muskmelons grown on calcareous soils. The data also reveal differences among K salts and suggest a reassessment of K management strategies aimed at improving quality.

Keywords: foliar fertilization; potassium; quality; cantaloupe; phytochemical

INTRODUCTION

Consumer preference for horticultural crops such as muskmelon (*Cucumis melo* L.) fruits is determined largely by quality traits such as taste (sugar content), flavor/aroma, texture, and, more recently, by their high ranking as rich sources of bioactive compounds with health-promoting properties.[1,2] These quality parameters are strongly influenced by crop genotype as well as environmental factors, especially nutrient management, during crop growth.[3]

Potassium (K) is well recognized as the essential plant nutrient with the strongest influence on many quality parameters of fruits and vegetables.[4] Although K is not a constituent of any functional molecules or plant structures, it is involved in numerous biochemical and physiological processes vital to plant growth, yield and quality.[4,5] In addition to stomatal regulation of transpiration and photosynthesis, K is also involved in photophosphorylation, transport of photoassimilates from source tissues via the phloem to sink tissues, enzyme activation, turgor maintenance, and stress tolerance.[4–7] Adequate K nutrition has also been associated with increased fruit size, increased soluble solids and ascorbic acid concentrations, improved fruit color, increased shelf life and shipping quality of many horticultural crops.[8–10]

Nearly all the K in plant tissues is taken up by roots from the soil solution as the monovalent cation (K^+), and uptake is regulated by plant and environmental factors.[5,11] Even though K is abundant in most calcareous soils, the bulk of soil K is unavailable to plants, in part, due to an imbalance between available Ca, Mg and K ions which can lead to K deficiencies through competitive uptake interactions.[11,12] Uptake of K from the soil solution also depends on plant factors, including genetics.[13] In many species, uptake occurs mainly during the vegetative stages when root growth is not inhibited by carbohydrate availability.[14] During reproductive growth stages, competition for photoassimilates between developing fruits and vegetative organs can limit root growth/activity and K uptake.[14] Therefore, soil-derived K, which is essential for fruit growth, yield and quality is not always optimal during the critical fruit development period, and this is partly responsible for poor fruit quality, and yield.[8,9] For field-grown plants, increasing soil K fertilization or perhaps amending soil pH, may not be enough to alleviate this developmentally induced deficiency, partly because of reduced growth/activity of roots

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and symbiotic organisms (myccorhizae) during reproductive development and also because of competition for binding sites on roots from other cations.[11,14,15] Commercial production practices such as high P fertilization and frequent soil disturbance during cultivation and tillage can disrupt myccorhizal hyphae and limit K uptake.

Previous controlled environment studies have shown that supplementing soil K supply with foliar K applications during the fruit development period can improve fruit quality and that differences may exist among K compounds for foliar feeding.[8,9] It is unclear, however, whether such positive responses can be realized under natural field conditions. Also, potassium chloride, a low-cost and most widely used fertilizer K salt, has a relatively high salt index which can limit its usefulness for foliar nutrition due to the increased risk of crystallization and salt injury.

The objectives of this multi-year study were to determine whether mid- to late-season foliar K applications during the fruit development and maturation stages can mitigate the developmentally induced K deficiency in field-grown muskmelon, thereby improving muskmelon fruit quality, and to determine whether differences exist among potential K salts for foliar feeding.

MATERIALS AND METHODS

Growth conditions

This study was conducted during the spring growing seasons (February–May) of 2005, 2006 and 2007 in fields located at the Texas AgriLife Research Center – Texas A&M System in Weslaco, (Texas (latitude 26° 9′ N, longitude 97° 57′ W; elevation 21 m). Soils in this region are predominantly calcareous (Table 1). The soil type at the study fields is a Hidalgo sandy clay loam, a common soil type in the region. In each study year, netted, orange-flesh muskmelon (*Cucumis melo* L. var 'Cruiser') was planted in early spring (February–March) and managed according to standard commercial practices for spring melon production which include raised beds covered with black plastic mulch, subsurface drip irrigation, nutrient management, and pest control. Plants were fertilized at the two-leaf stage with liquid N (50 kg N ha^{-1}; using urea ammonium nitrate, 320 g N kg^{-1}) and P (20 kg P ha^{-1}) fertilizers and again at the vine elongation stage with urea ammonium nitrate (50 kg N ha^{-1}). A foliar micronutrient fertilizer (Foli-Gro® Micro-Mix; Wilbur–Ellis, Co, Fresno, CA, USA) containing magnesium (Mg, 0.5 g kg^{-1}), boron (B, 2.5 g kg^{-1}), copper (Cu, 2.5 g kg^{-1}), iron (Fe, 5.0 g kg^{-1}), manganese (Mn, 5.0 g kg^{-1}), molybdenum (Mo, 0.025 g kg^{-1}), and zinc (Zn, 20 g kg^{-1}) was applied with foliar pesticide treatments at the vine elongation period at a rate of 4.6 L ha^{-1}. No additional soil K was added since pre-plant soil analyses indicated high K levels (1.2–2.0 cmol K kg^{-1}; Table 1). Microclimate data were monitored and recorded (Fig. 1) by a portable, automated weather station located within 100 m of the fields.

Foliar K treatments

Starting at fruit set, and continuing till fruit maturation, the following foliar K treatments were applied weekly: control (no K, de-ionized water), potassium chloride (KCl), potassium nitrate (KNO_3), potassium sulfate (K_2SO_4), and a glycine amino acid-complexed K (Potassium Metalosate™, KM, ∼7 mol L^{-1}; Albion Inc, Clearfield, UT, USA). In 2006 and 2007, two additional K sources, namely, monopotassium phosphate (PeaK™, ∼250 g kg^{-1}; Rotem LLC, Ft Lee, NJ, USA), and potassium thiosulfate (KTS™, ∼8 mol L^{-1}; Tessenderlo Kerley, Inc., Phoenix, AZ, USA) were included in the study. A non-ionic surfactant (Silwet L-77; Helena, Collierville, TN, USA) was added to all treatment solutions at 3 g active ingredient L^{-1}. Treatment solutions, except the control, were formulated to supply the equivalent of 3.7 kg K ha^{-1} in 378 L ha^{-1} spray volume during each application. All treatments were applied between 05.00 and 08.00 hours on each spray event using a tractor-mounted spray boom with multiple, calibrated spray heads and a multi-unit spray control system. A total of five foliar K applications per treatment were made each year.

Tissue sampling, fruit harvest and processing

At the onset of fruit maturation, leaf, petiole, and stem tissue samples were collected, rinsed with distilled water, dried (70 °C for 48 h), ground to pass a 40 µm screen and ashed (500 °C, 5 h), before K analysis by atomic absorption spectroscopy. In 2005, tissues were also collected before and after the onset of foliar K treatments for macro-nutrient analysis. During the harvest period, field plots were inspected every other day and matured (full slip) fruits were harvested between 06.00 and 09.00 hours over a 6–15 day period depending on year. At harvest, marketable fruits from each plot were weighed in bulk and then classified by size as small (≤0.14 m diameter or ≤1 kg), medium (0.15–0.16 m diameter or 1–2 kg) or large (≥0.17 m diameter or ≥2.0 kg). Ten uniform fruits (0.15–0.17 m diameter) were collected from each treatment during each harvest and stored at 4 °C for subsequent processing and analysis. The harvest date of each fruit batch was recorded. A previous fruit analysis from a companion study (Jifon and Lester, unpublished) revealed considerable variability in quality parameters based on fruit maturation/harvest date (early vs late harvest) and this tended to confound treatment effects. In that analysis, early-harvested fruit (or 'crown-set' fruits which are set near the base of the plant)[16] were more uniform in quality characteristics than late-harvested fruits. Fruit quality parameters in the present study

Table 1. Pre-plant soil chemical properties during each growing season

Year	pH	NO_3-N (10^{-3} g·kg^{-1})	K (10^{-3} g·kg^{-1})	P (10^{-3} g·kg^{-1})	Potassium activity ratios $\frac{[K^+]}{\sqrt{[Ca^{2+}]+[Mg^{2+}]}}$	$\frac{[K^+]}{\sqrt{[Mg^{2+}]}}$	$\frac{[K^+]}{\sqrt{[Ca^{2+}]}}$
2005	8.2a*	29.3a	664.7a	55.2a	0.27a	0.90a	0.28a
2006	8.3a	23.0a	612.0a	53.7a	0.24a	0.87a	0.25a
2007	8.4a	24.9a	572.7a	51.5a	0.22a	0.79a	0.23a

* Means within a column followed by the same letter are not significantly different using the Ryan-Einot-Gabriel-Welsch multiple-range test.

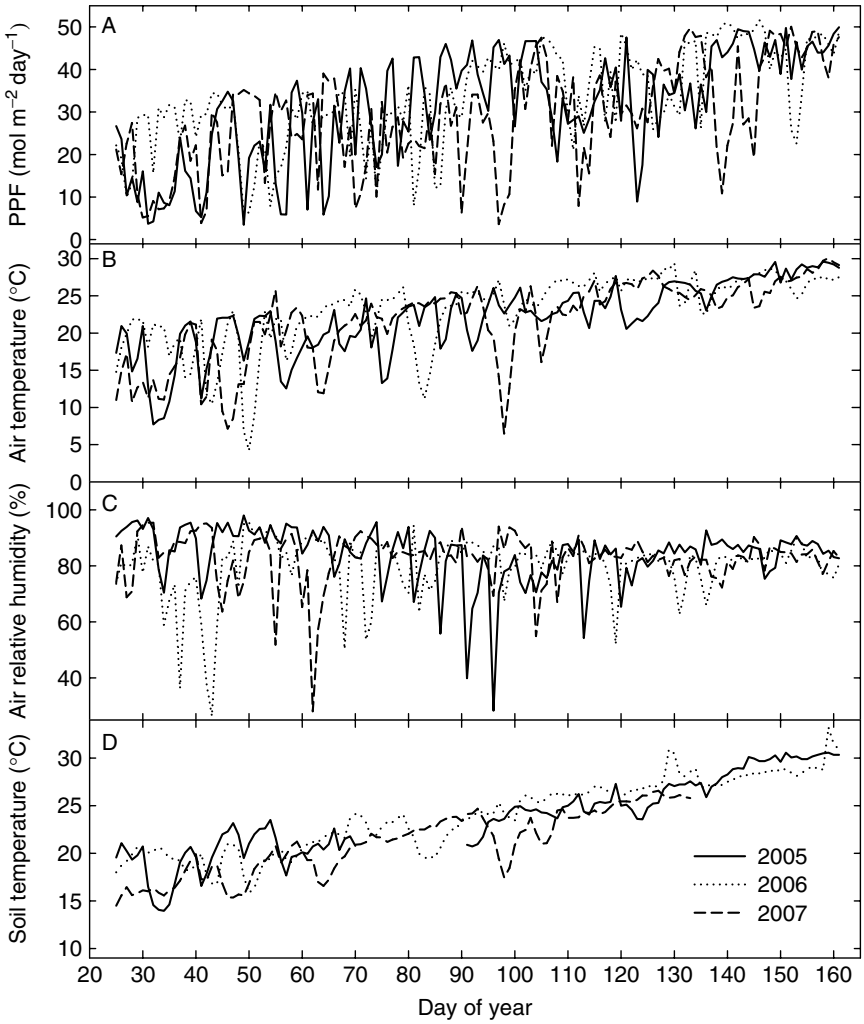

Figure 1. (A) Average daily photosynthetic photon flux (PPF), (B) air temperature, (C) relative humidity, and (D) soil temperatures during the growing seasons of 2005, 2006 and 2007 recorded at the study site.

were therefore analyzed based on maturity/harvest date, and, for brevity, only data from crown-set fruits in each year are reported. After harvest and initial cold storage, fruits selected for further processing were stored at 21 °C for 3 days (to simulate commercial retail display conditions) prior to internal fruit quality analyses. Fruits were individually weighed and middle mesocarp color characteristics and firmness were measured as in Lester *et al.*[8,9]

Fruit analysis

Fruit middle-mesocarp tissue samples were lyophilized and used for dry matter, K, soluble solids, total sugars (sucrose, glucose, fructose), ascorbic acid, and β-carotene analyses following procedures previously described in detail by Lester *et al.*[8,9] Briefly, juice samples expressed from fresh fruit tissue were analyzed for total soluble solids concentrations (SSC) using a temperature-corrected digital refractometer (Reichert Scientific Instruments, Buffalo, NY, USA). Fruit sugars (sucrose, glucose and fructose) were extracted from lyophilized tissue in 80% ethanol at 90 °C, and individual sugars determined using high-performance liquid chromatography (HPLC). Free ascorbic acid and dehydroascorbic acid were extracted with ice-cold meta-phosphoric acid and quantified by spectrophotometry, whereas β-carotene was extracted under low light conditions using ice-cold heptane and quantified by HPLC.

Statistical analysis

Experiments were set up in a randomized complete block design. Foliar K treatments were randomly assigned to plots within each block ($n = 4$) with each treatment appearing once per block (replication). Within a block, each plot (treatment) consisted of three adjacent rows (1.4 m wide by 15 m long) and data were collected from the central row. The effects of growing season (year), were analyzed with a two-factor analysis of variance (ANOVA) in a split-plot arrangement. The year effect (main-plot) was tested with the main plot experimental error (error a), whereas subplot (foliar K treatment) and interactive effects were tested with the subplot experimental error (error b)[17] using the general linear model procedures of SAS (Statistical Analysis System; SAS, Cary, NC, USA). For each year, treatment effects were further analyzed using the Ryan–Einot–Gabriel–Welsch (REGWQ) multiple-range test at the 95% probability level. Data are the average of five to ten single-fruit replications per K treatment.

Table 2. Influence of weekly foliar potassium applications during the fruit development period using various potassium salts on yield and fruit numbers (by size class) of field-grown muskmelon ('Cruiser'). Sizes were: small (≤0.14 m diameter or ≤1 kg), medium (0.15–0.16 m diameter or 1–2 kg) or large (≥0.17 m diameter or ≥2.0 kg)

Treatment (K salt)	Yield ($Mg \cdot ha^{-1}$)	Small ($\times 1000 \cdot ha^{-1}$)	Medium ($\times 1000 \cdot ha^{-1}$)	Large ($\times 1000 \cdot ha^{-1}$)	Culls ($Mg \cdot ha^{-1}$)
2005					
Control	19.2a*	3.4a	4.1a	1.4a	2.8b
Potassium chloride	20.9a	2.4a	4.5a	2.5a	1.6b
Potassium nitrate	18.8a	3.3a	4.0a	1.9a	6.8a
Potassium sulfate	23.1a	3.0a	5.6a	3.1a	1.5b
Potassium Metalosate	22.8a	1.9a	6.2a	2.1a	1.8b
P-values for K effect	0.791	0.538	0.730	0.548	0.002
2006					
Control	24.2a	3.2a	4.6a	1.7a	2.0b
Potassium chloride	25.7a	2.7a	5.2a	2.9a	1.3b
Potassium nitrate	22.8a	3.6a	4.8a	1.5a	3.6a
Monopotassium phosphate	24.5a	2.5a	6.5a	2.5a	1.7b
Potassium sulfate	27.8a	2.8a	5.9a	3.0a	1.3b
Potassium thiosulfate	28.7a	2.8a	7.0a	2.6a	1.9b
Potassium Metalosate	26.5a	2.6a	6.1a	2.9a	1.8b
P-values for K effect	0.882	0.917	0.700	0.343	0.014
2007					
Control	20.2b	6.2a	2.7a	1.4a	2.7b
Potassium chloride	22.5ab	5.5a	4.0a	2.0a	1.8b
Potassium nitrate	20.1b	6.1a	2.6a	1.6a	4.8a
Monopotassium phosphate	23.5ab	4.6a	3.3a	2.1a	2.3b
Potassium sulfate	22.9ab	5.2a	2.4a	2.4a	1.7b
Potassium thiosulfate	25.5a	5.4a	2.5a	1.9a	2.5b
Potassium Metalosate	23.2ab	5.1a	3.3a	2.1a	2.4b
P-values for K effect	0.037	0.684	0.922	0.737	0.010
P-values for year effect	<0.001	<0.001	<0.001	0.011	0.080
Year × K treatments	0.799	0.699	0.756	0.894	0.429

* Means within a column and within a year followed by the same letter are not significantly different using the Ryan–Einot–Gabriel–Welsch multiple-range test.

RESULTS

Weather conditions during the three growing seasons differed substantially especially during the fruit development and maturation period (Fig. 1). In 2007, planting was delayed by approximately 3 weeks due to unusual cool weather conditions in January and February. The total growing season durations from planting to final harvest were 113, 91 and 94 days in 2005, 2006 and 2007, respectively. The corresponding fruit development and maturation durations were 42, 46 and 31 days, respectively. Cumulative heat units during the fruit development and maturation periods 2005, 2006 and 2007 were 830, 781 and 871, respectively whereas the cumulative photosynthetic photon flux values were 1520, 1702 and 1266 mol m^{-2}, respectively.

Yield

Fruit yields ranged from 18 to 28 Mg ha^{-1} and were generally highest in 2006 than in 2005 or 2007 (Table 2). Even though foliar K-treated plots had slightly higher yields in all three study years, a significant yield increase was recorded only in 2007 with potassium thiosulfate. Yield differences among K salts were generally not significant, except in 2007 where average yields from plots treated with potassium thiosulfate were significantly higher than those treated with KNO_3. Individual fruit fresh weights, dry matter contents and size distribution were not affected by K treatments. Significantly more non-marketable fruits (culls) were harvested from KNO_3-treated plots than from plots treated with the other K salts.

Tissue mineral contents

Tissue K concentrations were generally higher in 2007 than in 2005 and 2006 ($P < 0.001$ for year effect; Table 3). At fruit maturity, average tissue K concentrations in treated plants were approximately 17–21% higher than those of control plants ($P < 0.001$; Table 3). In 2005, plants treated with Potassium Metalosate had the highest tissue K values; however, this effect was not always significant when compared to the other K salts evaluated. In 2006 and 2007, there were no consistent trends among the K salts except for KNO_3 which tended to result in the lowest relative increases in tissue K.

Regardless of K treatment, tissue N, P, K and S were significantly lower at fruit maturity than before fruit set (Table 4). On the other hand, tissue Ca and Mg were higher during the later growth stages than in the vegetative stages. Foliar K treatments generally had no effects on tissue macro-nutrients, with the exception of leaf nitrogen (N), and leaf, petiole and stem K and Mg concentrations. Foliar fertilization with KNO_3 significantly increased leaf and petiole

Table 3. Tissue potassium concentrations (dry mass basis) of field-grown muskmelons ('Cruiser') determined at fruit maturity following weekly foliar applications of potassium during the fruit development period using various salts: potassium chloride; potassium nitrate; monopotassium phosphate, Peak™; potassium sulfate; potassium thiosulfate, KTS™; and potassium Metalosate™, KM. Peak and KTS were added to the study in 2006 and 2007

Treatment (K salt)	Leaf K ($g \cdot kg^{-1}$)	Petiole K ($g \cdot kg^{-1}$)	Stem K ($g \cdot kg^{-1}$)	Fruit mesocarp K ($g \cdot kg^{-1}$)
2005				
Control	12.5b*	32.5c	27.7b	22.0d
Potassium chloride	14.1a	40.2b	33.8ab	26.0bc
Potassium nitrate	13.5ab	41.7ab	31.4ab	24.3cd
Potassium sulfate	13.9a	42.2ab	31.6ab	29.6a
Potassium Metalosate	14.4a	47.1a	38.5a	28.2ab
Significance of K effect	0.004	<0.001	0.016	<0.001
2006				
Control	10.7b	48.2d	42.9d	26.2b
Potassium chloride	11.6ab	55.0bc	49.1c	33.5a
Potassium nitrate	11.9ab	47.5d	41.5d	29.2ab
Monopotassium phosphate	12.9ab	51.6cd	46.5cd	33.9a
Potassium sulfate	14.6a	50.2d	64.0a	31.4a
Potassium thiosulfate	13.5ab	64.2a	55.3b	32.4a
Potassium metalosate	14.3a	57.8b	48.0c	34.0a
P-values for K effect	0.005	<0.001	<0.001	<0.001
2007				
Control	12.9b	55.1b	46.0d	21.9c
Potassium chloride	14.0ab	63.3ab	53.9c	24.1bc
Potassium nitrate	13.1b	55.3b	47.8d	22.9bc
Monopotassium phosphate	15.8ab	61.3ab	53.6c	24.6bc
Potassium sulfate	14.9ab	59.7ab	69.6a	25.6b
Potassium thiosulfate	16.7a	73.8a	63.8b	29.2a
Potassium metalosate	15.3ab	66.5ab	53.6c	25.6b
P-values for K effect	0.019	0.01	<0.001	<0.001
P-values for year effect	0.003	<0.001	<0.001	<0.001
Year × K treatments	0.246	0.624	0.624	<0.011

* Means within a column and within a year followed by the same letter are not significantly different using the Ryan–Einot–Gabriel–Welsch multiple-range test.

N concentrations but resulted in reduced Mg concentrations in petioles and stems.

Soluble solids and sugars

Average fruit SSC and sugars (sucrose, glucose and fructose) were generally higher in 2005 and 2006 (8–11°Brix) than in 2007 (8–10°Brix; $P < 0.001$ for year effect; Table 5). Foliar K treatments increased fruit SSC in all three years; however, total fruit sugars were significantly increased only in 2005 and 2006, reflecting the trends observed for fruit sucrose, the dominant sugar component. Fruit fructose concentrations were the most responsive to K treatments and were consistently increased in all three years following foliar K applications. In 2005 and 2006, significant differences were observed among K sources, with fruit from plants treated with potassium metalosate generally having the highest total sugar concentrations and relative sweetness indices, whereas KNO_3-treated fruit generally had the lowest values.

Bioactive compounds

Fruit bioactive compounds (ascorbic acid and β-carotene) were generally higher in 2005 and 2006 than in 2007 ($P < 0.001$ for year effect; Table 6) and were increased by foliar K treatments; however, foliar K effects were significant only in 2005 and 2006. In 2006, significant differences were observed among K sources, with fruit from plants treated with potassium metalosate generally having the highest total ascorbic acid (TAA) and β-carotene concentrations. In 2005 and 2007, however, differences among K sources were generally not significant. In all three years, foliar K-treated fruits were more intensely orange-colored, as indicated by their lower hue angles compared to those of controls. External fruit firmness was increased by foliar K applications only in 2005 and 2006 whereas internal firmness was increased by foliar K applications in all three years. As with tissue K and sugars, there were no consistent differences among K sources in fruit firmness or color except for KNO_3-treated fruit which tended to have the lowest firmness values and highest hue angles.

DISCUSSION

Even though fruit yields from foliar K-treated field plots were slightly higher than those from control plots, this K effect was only significant in 2007. Given the high soil exchangeable K (K_{ex}) of this soil, the largely non-significant yield responses are not surprising. Hartz *et al.*[18] found that K fertigation (supplemental K injected into the irrigation water) increased tomato fruit yields even when K_{ex} was high, but found no effect of foliar K applications on yield and quality. In another study, Hartz *et al.*[19] also found no

Table 4. Tissue mineral contents (dry mass basis) of field-grown muskmelon ('Cruiser') determined during the 2005 growing season before fruit set (pretreatment) and at fruit maturity following weekly foliar applications of potassium during the fruit development period using various potassium salts

Treatment (K salt)	Nitrogen ($g \cdot kg^{-1}$)	Phosphorus ($g \cdot kg^{-1}$)	Potassium ($g \cdot kg^{-1}$)	Magnesium ($g \cdot kg^{-1}$)	Calcium ($g \cdot kg^{-1}$)	Sulfur ($g \cdot kg^{-1}$)
Leaves						
Pretreatment	35.0a*	4.8a	37.1a	5.5b	38.4b	9.0a
Control	21.8c	1.7b	12.5c	8.9a	98.8a	6.5b
Potassium chloride	24.3c	1.9b	14.1b	9.8a	104.4a	6.3b
Potassium nitrate	30.6b	2.1b	13.5bc	9.1a	99.4a	6.6b
Potassium sulfate	22.3c	1.8b	13.9b	9.4a	105.0a	7.4b
Potassium Metalosate	22.5c	2.0b	14.4b	9.3a	110.3a	6.5b
P-values for K effect	0.011	0.682	0.004	0.479	0.589	0.487
Petioles						
PreTreatment	33.0a	4.2a	126.9a	4.7c	22.7b	2.7a
Control	13.3c	0.9b	32.5d	9.0a	62.3a	2.1a
Potassium chloride	14.3c	1.2b	40.2c	9.2a	60.3a	1.5a
Potassium nitrate	25.5b	1.3b	41.7bc	7.9b	56.1a	1.7a
Potassium sulfate	13.8c	1.0b	42.2bc	9.1a	60.4a	2.2a
Potassium metalosate	13.8c	1.2b	47.1b	8.8ab	60.1a	2.3a
P-values for K effect	0.036	0.247	<0.001	0.017	0.245	0.307
Stems						
PreTreatment	25.7a	5.1a	89.0a	4.0b	10.0b	2.1a
Control	11.5b	1.3b	27.7c	5.7a	20.0a	2.1a
Potassium chloride	13.5b	1.6b	33.8bc	5.5a	20.2a	2.1a
Potassium nitrate	14.0b	1.9b	31.4bc	4.6a	17.5a	2.2a
Potassium sulfate	12.3b	1.5b	31.6bc	5.9a	20.1a	2.4a
Potassium metalosate	11.8b	1.8b	38.5b	5.0a	18.5a	2.2a
P-values for K effect	0.586	0.264	0.016	0.193	0.124	0.785

* Means within a column and within a year followed by the same letter are not significantly different using the Ryan–Einot–Gabriel–Welsch multiple-range test.

tomato yield or quality responses to foliar K fertilization, even though K fertigation increased fruit yields in instances where $K_{ex} < 0.35$ cmol kg^{-1}. It is worth noting that although Hartz *et al.*[19] also applied foliar K during the fruit development period, KNO_3 was the sole K salt used, which in the present study resulted in non-significant effects on fruit quality and yield. Improved stress tolerance, resulting from increased plant K status and increased antioxidant (TAA and β-carotene) levels following foliar K treatments, potentially protected plants from the stressful growth conditions, especially in 2007 thus accounting for the relative yield increase.

Salt crystallization and injury (leaf 'burn') symptoms were not observed with any of the treatments, in part, because all treatments were applied early in the mornings when high air relative humidities (>80%), low air temperatures (<25 °C) and low wind speeds (<1 mph) prevailed. Phytotoxicity symptoms resulting from foliar chemical applications are often reported when compounds with high salt indices (for example KCl, approx. 120)[20] and relatively high point of deliquescence are applied under conditions of high temperature and/or low humidity.[21,22] The current observations indicate that the experimental conditions (solution concentrations and timing) during foliar K applications in this study were adequate for minimizing residue formation and salt injury.

Plant K requirements are known to change over time with development, and uptake rates must also change to match demand.[4,5,10] Optimum K concentrations in plant foliage are usually in the range of 15–35 g kg^{-1} dry mass. The significant reduction in tissue K concentrations between vegetative and reproductive growth stages, and the observed positive responses of tissue K concentrations to foliar K applications indicate that plant K uptake from this calcareous soil was not sufficient to satisfy plant K requirements and that the K supplying power of this soil is low even though pre-plant soil K content was high. The low K supplying capacity of this soil is further indicated by the high pH and high Ca and Mg concentrations (Table 1) since these conditions are known to suppress crop K uptake, presumably, through competitive and antagonistic uptake mechanisms.[5,11,12] Soil K activity ratios ranged from 0.22 to 0.90, and were within the range of activity ratios reported by Hartz *et al.*[23] who found that tomato K concentrations and quality parameters were better correlated with K activity ratios than with soil exchangeable K alone. Reduced root growth and activity resulting from competition for photoassimilates between roots and stronger sinks (fruits) can also contribute to limited root K uptake during the fruit development period[14] and hence to the positive response of tissue K to foliar applications.

The overall effects of foliar K applications on tissue mineral concentrations, other than K, were minimal, indicating that the observed effects were not due to the non-K components of the K salts used, with the exception of KNO_3. Foliar fertilization with KNO_3 during the fruit development stages significantly increased leaf and petiole N concentrations but reduced Mg concentrations in petioles and stems probably due to a dilution effect resulting

Table 5. Mesocarp soluble solids concentrations (SSC), sugar contents (fresh mass basis) and relative sweetness of field-grown muskmelon ('Cruiser') fruit following weekly foliar applications of potassium during the fruit development period using various potassium salts

Treatment (K salt)	SSC (°Brix)	Sucrose (g·kg^{-1})	Fructose (g·kg^{-1})	Total sugars* (g·kg^{-1})	Relative sweetness†
2005					
Control	8.2c*‡	24.0b	13.1b	47.2c	54.7c
Potassium chloride	10.5ab	31.3a	16.5ab	59.3ab	69.2ab
Potassium nitrate	8.9bc	25.7b	14.7b	50.5bc	59.2bc
Potassium sulfate	11.2a	28.7ab	18.1a	59.1ab	70.0ab
Potassium Metalosate	10.1ab	31.5a	18.2a	62.1a	73.0a
P-values for K effect	<0.001	0.002	0.002	0.003	0.003
2006					
Control	9.0c	29.1b	13.7b	53.2d	61.1c
Potassium chloride	10.3ab	31.1b	18.0ab	61.4bcd	72.1bc
Potassium nitrate	9.1bc	30.2b	14.1b	54.7cd	62.9c
Monopotassium phosphate	10.3ab	32.5ab	22.0a	67.3abc	81.1ab
Potassium sulfate	10.6a	38.2a	19.3a	72.5ab	83.5ab
Potassium thiosulfate	11.2a	35.0ab	22.4a	69.1ab	81.3ab
Potassium Metalosate	10.6a	38.6a	22.5a	76.3a	89.8a
P-values for K effect	<0.001	<0.001	<0.001	<0.001	<0.001
2007					
Control	8.0c	20.3a	9.9b	36.7a	42.7a
Potassium chloride	9.8ab	22.3a	14.5a	44.5a	53.8a
Potassium nitrate	8.5bc	21.3a	11.7ab	39.9a	47.2a
Monopotassium phosphate	10.0a	22.9a	14.0a	44.3a	53.3a
Potassium sulfate	9.7ab	23.3a	14.1a	45.0a	54.1a
Potassium thiosulfate	10.1a	22.7a	13.8a	43.8a	52.7a
Potassium Metalosate	9.4abc	23.2a	14.1a	44.7a	53.7a
P-values for K effect	<0.001	0.852	0.027	0.348	0.196
P-values for year effect	0.002	<0.001	<0.001	<0.001	<0.001
Year × K treatments	0.670	0.08	0.105	0.115	0.160

* Total sugars = sucrose + glucose + fructose.
† Relative sweetness = (1.8 × [fructose]) + (0.7 × [glucose]) + (1.0 × [sucrose]).
‡ Means within a column and within a year followed by the same letter are not significantly different using the Ryan–Einot–Gabriel–Welsch multiple-range test.

from N stimulation of vegetative growth at the expense of roots and fruits.[24]

Fruit sugar content, a key consumer preference trait, and bioactive compounds (ascorbic acid and β-carotene) responded positively to foliar K applications in two of the three study years. Although the mechanisms for these improvements are uncertain, key metabolic processes that have been associated with these parameters such as improved leaf photosynthesis and sugar production, phloem loading/unloading, photoassimilate transport from leaves to fruits, improved leaf and fruit water relations, increased enzyme activation and substrate availability for ascorbic acid and β-carotene biosynthesis, have also been linked with increased plant K status.[4–7,25] The relatively low sugar contents in 2007 were likely due to reduced leaf CO_2 assimilation rates resulting from frequent cloudy weather conditions in that year (Fig. 1). These weather conditions delayed planting, canopy development, and fruit set, leading to a reduction in the fruit development and maturation period.

A wide range of observations, including positive and negative responses, of crop quality to K fertilization have been reported in the literature.[4,6,7,26,27] In an evaluation of the effects of K fertilization on yield and quality of processing tomato (*Lycopersicon esculentum* Mill.), Hartz *et al.*[18,19] found that K fertigation reduced the incidences of yellow shoulder and internal white tissue disorders in tomato but did not influence fruit SSC, even though K_{ex} ranged from 0.2 to 0.8 cmol kg^{-1}. They attributed the absence of any response of fruit SSC to factors unrelated to soil K supply such as cultivar and irrigation management which potentially masked any K effects, and concluded that under California field conditions (K_{ex} > 0.35 cmol kg^{-1}), fruit SSC and juice color do not respond to K fertilization. In the present study, K_{ex} ranged from 1.2 to 2 cmol kg^{-1}; however, the levels of antagonistic cations, Ca^{2+} (~35 cmol kg^{-1}) and Mg^{2+} (~4.5 cmol kg^{-1}), were also very high, potentially limiting soil K supply and thus accounting for the response to late-season foliar K applications.

Previous controlled-environment studies by Lester *et al.*[8,9] suggested that the relative fruit quality enhancements resulting from mid- to late-season foliar K applications were greater when an organic form of K (Potassium Metalosate) was used compared to an inorganic (KCl) source. In the current field study, although fruit quality enhancements associated with Potassium Metalosate were among the highest observed (Tables 5 and 6), differences among K salts were not always significant or consistent. All the K salts evaluated were effective in enhancing fruit quality parameters compared to controls; the exception being KNO_3 whose effects

Table 6. Influence of weekly foliar potassium applications using various potassium salts on fruit mesocarp total ascorbic acid (TAA) concentrations, β-carotene concentrations (fresh mass basis), internal color and firmness of field-grown muskmelon ('Cruiser'). Foliar potassium applications were made during the fruit development and maturation stages

Treatment (K salt)	TAA (10^{-2} g·kg^{-1})	β-Carotene (10^{-3} g·kg^{-1})	Mesocarp color (h°)	Internal firmness (N)	External firmness (N)
2005					
Control	30.3c*	14.2b	72.8a	12.7b	51.9b
Potassium chloride	33.2abc	18.8a	71.8ab	17.1a	63.0ab
Potassium nitrate	31.6bc	16.7ab	71.9ab	14.5ab	52.6b
Potassium sulfate	35.5a	18.1a	71.3b	15.4ab	53.6ab
Potassium Metalosate	34.5ab	18.0a	71.2b	16.2a	66.7a
P-values for K effect	0.001	0.014	0.048	0.003	0.014
2006					
Control	19.3c	18.3b	72.7a	10.6b	31.5b
Potassium chloride	22.8a	21.1ab	72.2ab	11.8ab	55.1a
Potassium nitrate	20.0bc	18.0b	72.4ab	10.1b	31.2b
Monopotassium phosphate	21.4abc	21.3ab	72.0ab	13.7a	40.0ab
Potassium sulfate	22.1ab	19.8ab	72.1ab	11.9ab	40.0ab
Potassium thiosulfate	22.4ab	21.1ab	71.3b	13.2a	42.7ab
Potassium Metalosate	23.7a	23.9a	71.7ab	12.7a	44.8ab
P-values for K effect	<0.001	0.003	0.036	<0.001	0.017
2007					
Control	15.7a	10.3b	73.0a	8.5b	44.2a
Potassium chloride	16.7a	11.1ab	71.9abc	10.3ab	47.2a
Potassium nitrate	16.9a	10.8ab	72.8ab	8.7b	44.4a
Monopotassium phosphate	17.1a	11.5ab	71.6c	11.0a	52.8a
Potassium sulfate	18.1a	10.9ab	72.2abc	10.6ab	56.5a
Potassium thiosulfate	18.6a	11.6ab	72.3abc	11.2a	55.7a
Potassium Metalosate	18.4a	13.0a	71.9bc	11.3a	55.1a
P-values for K effect	*0.543*	*0.046*	*0.004*	*0.002*	*0.328*
P-values for year effect	<0.001	<0.001	0.058	<0.001	<0.001
Year × K treatments	0.617	0.099	0.335	0.270	0.269

* Means within a column and within a year followed by the same letter are not significantly different using the Ryan–Einot–Gabriel–Welsch multiple-range test.

were nearly always statistically similar to those of controls. While KNO_3 is a suitable K source for foliar feeding during vegetative growth stages, its potentially negative effects on fruit quality parameters when applied during the fruit development stages may preclude its usefulness for foliar K feeding to improve fruit quality on calcareous soils.[24]

Plausible mechanisms for the K-induced increase in fruit ascorbic acid and β-carotene contents include increased synthesis through enzyme activation as well as increased substrate (carbon skeletons) availability,[28,29] resulting from K-induced improvements in fruit sugar content. This is the first report to our knowledge of K fertilization improving the bioactive components of field-grown muskmelons.

Fruit firmness, a good indicator of shipping quality, texture and shelf life of much horticultural produce,[30] was also increased by foliar K feeding. It is unlikely, however, that this foliar K-related increase in fruit firmness is due to increased cell wall integrity, as is the case with exogenously applied Ca, since K does not form part of any structural components of plant tissues as does Ca.[31,32] Lester *et al.*[9] found that fruit firmness was closely correlated with fruit tissue pressure potential (ψ_p), with fruit from K-treated plants having significantly higher ψ_p values than those of control plants, presumably due to increased fruit osmotica (sugars and K). Increased firmness of K-treated fruit could also be an indirect consequence of enhanced phloem transport of Ca to fruits following K applications.

CONCLUSIONS

The current data demonstrate that supplementing soil-derived K with foliar K applications during the fruit development and maturation period can improve fruit quality parameters, including bioactive compounds, of muskmelons grown on calcareous soils. All the foliar K sources evaluated, except for KNO_3, were effective in improving fruit quality. Due to the stimulating effect of N on vegetative growth, it is recommended that the use of KNO_3 be restricted to vegetative growth stages. The observed fruit quality improvements, and variability among foliar K salts underscore the need to reassess soil K management strategies to improve fruit quality especially on calcareous soils. Alternative strategies such as increasing soil fertilizer K applications, amending soil pH, and/or encouraging symbiotic associations (myccohizae) could also be utilized in conjunction with foliar K feeding. Compared to soil intervention strategies for dealing with the K availability problem, foliar K feeding is a practice that growers can easily incorporate into existing foliar pesticide treatments using existing equipment.

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