

Potassium Management for Optimizing Citrus Production and Quality

Ashok K. Alva
Dirceu Mattos, Jr.
Siva Paramasivam
Bhimu Patil
Huating Dou
Kenneth S. Sajwan

ABSTRACT. Potassium (K) is highly mobile in plants at all levels, that is, from individual cell to xylem and phloem transport. This cation plays a major role in (1) enzyme activation; (2) protein synthesis; (3) stomatal function; (4) stabilization of internal pH; (5) photosynthesis; (6) turgor-related processes; and (7) transport of metabolites. Citrus trees generally do not show visible deficiency symptoms across a wide range of K status in the leaves, except when the leaf concentrations drop below 3-4 mg kg⁻¹. However, fruit quality is quite sensitive to varying levels of K availability. High levels of K cause large fruit size with thick and coarse

Ashok K. Alva is Research Leader, USDA-ARS-PWA, Vegetable and Forage Crops Research Unit, 24106 North Bunn Road, Prosser, WA 99350-9687 (E-mail: aalva@pars.ars.usda.gov).

Dirceu Mattos, Jr., is affiliated with Centro Citros Sylvio Moreira-IAC, Rod. Anhanguera, Km 158, 13490-970 Cordeirópolis, SP, Brazil (E-mail: ddm@centro-decitricultura.br).

Siva Paramasivam and Kenneth S. Sajwan are affiliated with Savannah State University, Environmental Sciences & Biotech Research, Drew Griffith Hall, Savannah, GA 31404 (E-mail: siva@tigerpaw.savstate.edu).

Bhimu Patil is affiliated with Texas A&M University, Vegetable and Fruit Improvement Center, Department of Horticultural Sciences, 1500 Research Parkway, Suite A120, College Station, TX 77845 (E-mail: b-patil@tamu.edu).

Huating Dou is affiliated with Florida Department of Citrus, 700 Experiment Station Road, Lake Alfred, FL 33850 (E-mail: hdou@citrus.state.fl.us).

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peel. In contrast, K deficiency produces smaller fruits with thin peel. With regard to juice properties, K nutrition has a significant role in juice acidity; that is, high juice acidity with high K availability, while low K availability causes decrease in juice acidity. High K availability in the soil can reduce the uptake of other cations, primarily magnesium, calcium, and ammonium N. In this paper, the available information on the effects of varying availability of K on the fruit yield, postharvest quality of fruit, as well as juice quality is summarized. The current recommendations on the application of soil and leaf analysis for evaluation of the K nutritional status and guidelines for K fertilization are also discussed.
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INTRODUCTION

Citrus is grown in several parts of the world, where minimum temperatures stay above -4°C (Spiegel-Roy and Goldschmidt, 1996). The worldwide production of citrus, about 102 million metric tonnes per year, is much greater than that of other tropical and subtropical fruits, including banana, mango, apple, pear and peach. The majority of the total world production of the best internal quality fruit is produced in the subtropical region. Brazil and the United States combined account for up to 45% of total world orange production, while the United States accounts for up to 40% of grapefruit production in the world (FAO, 2004). Average annual production of oranges in Brazil is 15 million tonnes, which represents 30% of the world production. Around 80% of this total fruit production is processed into orange juice by more than 10 concentrated and frozen juice-processing plants located in the state of Sao Paulo, which encompasses the country's major citrus production region. It is estimated that 2-3 million tonnes per year supply the fresh fruit market, which includes production of oranges, 'Ponkan' and 'Rio' tangerines, 'Murecott' tangor, and 'Tahiti' acid lime.

Although citrus production extends over a wide range of soils, sandy to clay loam soils are best suited for production of high yields of high quality fruits. Adequate soil drainage is an important factor for good

tree growth. Citrus is planted on raised beds in high rainfall areas with fine textured soils, where drainage would be a problem. Soil pH is an important factor that influences nutrient availability and other soil chemical and biological processes. Soil pH of 6.0 is optimal for citrus production, however, a soil pH range of 5.5-7.5 can support adequate growth of citrus trees, depending on the rootstock used. In soils with high copper concentrations, pH may be raised to 6.5 (Alva et al., 1995). In areas of Sao Paulo, Brazil, citrus is grown in tropical soils with pH range of 4.8-5.5.

To underscore the importance of maintaining a flourishing citrus industry, there is a need to establish sustainable production management systems that can support optimal production of fruits with minimal negative impacts on the environment. This philosophy takes into account best management practices (BMP) of agricultural resources to improve the efficiency of fertilizer inputs by minimizing the losses (Havlin et al., 1999). Therefore, BMPs for nutrients imply improved utilization of nutrients with adequate use of rates, timing, and placement of fertilizer, combined with optimal scheduling of irrigation.

In this review, the available research information/recommendations on the effects of varying availability of potassium (K) on the yield and quality of oranges and grapefruits are summarized. The application of soil and leaf analysis for evaluation of K nutritional status, as well as K fertilization guidelines are discussed. An abbreviated version of discussion on some aspects of K fertilization for sustainable citrus production is presented elsewhere (Alva et al., 2001). Potassium regulates several enzyme functions, plant water relations, electrochemical equilibrium of cells, and carbohydrate transport of vascular plants (Marschner, 1995). In addition, K plays an important role in maintenance of cell turgor and extensibility that affects fruit size. Since K is highly mobile in plants, it is found in high concentrations in growing parts including leaves, flowers, and fruits.

The early work of Chapman et al. (1947) using large solution culture chambers, and Smith et al. (1953) in sand culture provided basis to show the K need for citrus tree growth and fruit production. In both studies, no growth difference was observed when the leaf K concentration was within 5-24 g kg⁻¹. However, K deficient trees had smaller leaves, fine branches, and more compact appearance. Trees supplied with excess K, that is, with leaf K content > 35 g kg⁻¹, also grew poorly. Potassium deficient trees produce small fruits, often with poor color and thin rind. Under severe deficiency, fruit drop could occur. Deficiency of K results in scorching of the leaf edge and sections between the veins (Brian, 1957).

Recent studies demonstrated significant correlations of fruit production with either soil exchangeable K or leaf K concentrations.

There is a strong relationship between fruit quality and K availability. Studies have demonstrated marked effects of K supply on fruit size and rind thickness. Increased fruit size is a favorable trait for the fresh fruit market. The fruit becomes larger and coarser as the K level increases. Low availability of K reduced fruit size of all citrus varieties.

DIAGNOSIS OF POTASSIUM NUTRITIONAL STATUS

Nutrient Requirement

Seasonal uptake of K by citrus trees is very low during cooler months and increases rapidly following the resumption of new growth and bloom in the spring (Roy and Gardner, 1946). Furthermore, nitrogen (N) and K in the fruits represent the largest component of the nutrients removed from the soil by the tree on an annual basis. Other nutrients, for example calcium, are present in large amounts in the structural framework of trees formed by woody tissue and old leaves (Mattos Jr. et al., 2003c). Nutrients removed by harvesting the fruits must be replenished. The amount of nutrients removed by different citrus species varies from a few grams per tonne of fruits as in the case of metal ions to as much as 2 kg per tonne of fruits for N and K (Bataglia et al., 1977; Mattos Jr. et al., 2003b,c; Alva and Paramasivam, 1998a) (Table 1). Alva and Paramasivam (1999a) analyzed the total nutrient content in the fruits of sweet orange cultivars grown under commercial production management conditions in Florida. Using the nutrient contents in the fruits, the total K removed from a grove with 80 Mg ha⁻¹ production potential were calculated for different citrus cultivars. Accordingly, the K removed in the fruits of 'Hamlin', 'Parson Brown', 'Valencia', and 'Sunburst' cultivars were 121, 118, 129, and 124 kg ha⁻¹ yr⁻¹. In addition to the nutrients removed on an annual basis in the harvested fruits, the continued maintenance of the tree and annual new growth (i.e., new leaf and root flush) also require nutrients on an annual basis. Potassium content measured in different parts of 6-year-old 'Hamlin' orange trees, planted at 286 trees ha⁻¹, accounted for 52 kg ha⁻¹. Of this total amount, about 28 kg ha⁻¹ of this element was found in leaves, stem, trunk, and roots (Mattos Jr. et al., 2003c). Over the long term, a portion of tree storage nutrients contribute to the annual fruit production. Therefore, the annual nutrient requirement should account for that portion of the nutrients,

TABLE 1. Total amount of various nutrients¹ in tonne (Mg = megagram or tonne) of oranges.

Nutrient Elements	kg Mg ⁻¹ of Fruits
N	1.2-1.9
P	0.18
K	1.2-1.9
Ca	0.52
Mg	0.10
S	0.10
Fe	3.4×10^{-3}
B	1.9×10^{-3}
Zn	1.7×10^{-3}
Mn	1.9×10^{-3}
Cu	0.6×10^{-3}

¹Based on data from Bataglia et al. (1977), Mattos Jr. et al. (2003a), and Alva and Paramasivam (1998a).

which contributes to the tree storage and that which is required for the annual fruit production. Fertilizer application rate, however, should adjust the nutrient requirement for application efficiency.

Alva et al. (2003) conducted a study to determine the partitioning of K in different parts of 3-year-old 'Hamlin' orange trees on 'Swingelo citrumelo' rootstock grown on a sandy soil with under-the-tree sprinkler irrigation. The trees received N, P, and K fertilizers during the first 3 years of growth as either water soluble granular (WSG:4 applications per year), fertigation (FRT:15 applications per year), or controlled-release fertilizer (CRF:1 application per year). The rates of N, P, and K were adjusted each year to compensate for the tree growth. The rates of individual nutrients for a given year were similar across different sources. However, partitioning of K (within the tree) into leaves was greater for the trees that received fertilizer as FRT as compared with that of the trees receiving either WSG or CRF sources (Table 2). Partitioning of K in the tree trunk was much greater in the trees that received CRF as compared with that in the trees receiving either WSG or FRT sources. These variations in K partitioning with using different sources of fertilizers were not, however, dependent on the variations in dry matter partitioning (Table 2). The study provided no clues as to the reasons for the above variations. Partitioning of K in the roots was greater in the trees that received WSG source of fertilizer as compared with that in the trees with either FRT or CRF sources.

TABLE 2. Percentage of partitioning of dry matter and potassium (K) in different parts of 3-year-old 'Hamlin' orange trees on 'Swingleo citrumeo' rootstock grown on a sandy soil, which received N, P, and K fertilizers as either water soluble granular (WSG), fertigation (FRT), or controlled release form (CRF) sources.

Tree parts	WSG		FRT		CRF	
	Dry Matter	K	Dry Matter	K	Dry Matter	K
Leaves	19	24	20	34	15	17
Trunk	18	12	30	13	30	26
Small Branches ¹	9	12	11	20	8	9
Large Branches ²	18	15	13	6	20	19
Small Roots ³	13	21	13	13	14	13
Large Roots ⁴	13	16	13	14	13	16

Note:

¹Diameter < 1 cm

²Diameter > 1 cm

³Fibrous or feeder roots

⁴Branch roots

Source: Adapted from Alva et al. (2003).

Nutrient uptake from applied fertilizers is not 100% efficient, so more nutrients must be applied than the minimum required by the tree. For example, N use efficiency ranges from 20 to 40% in groves with low to moderate yield, and rarely exceeds 50% even in highly productive groves (Legaz et al., 1981; Dasberg, 1987; Feingenbaum et al., 1987; Mattos Jr. et al., 2003a) due to NO_3^- -leaching, ammonia volatilization and other losses (Syvertsen and Smith, 1996; Paramasivam et al., 1999; Cantarella et al., 2003; Mattos Jr. et al., 2003b). In sandy soils, K is also subject to leaching losses as is the case with NO_3^- (McNeal et al., 1995). Improved nutrient and irrigation management practices, such as improved placement of fertilizers, that is, under-the-tree canopy, and optimal irrigation scheduling are important to minimize leaching losses. These include split application of nutrients 3-5 times during the growing period to minimize loading the soil with single application of a large dose of nutrient which promotes leaching losses. The increased adaptation of fertigation technique provides a convenient and cost-effective avenue for split application of N and K with 3-5 or more applications per year.

Soil Sampling and Analysis

Soil testing has been used for fertilizer recommendations of crops based on the calibration of results of soil analysis with crop response to

applied nutrients (Nelson and Anderson, 1977; Cantarella et al., 1998; Havlin et al., 1999). The successful use of soil analysis depends on proper sampling and handling techniques (Petersen and Calvin, 1996). Each soil sample should consist of a composite of soil cores taken from a particular depth and area in the grove. The general sampling technique should be modified under certain circumstances in order to allow collection of representative soil samples. For example, in micro-irrigated groves sampling should be taken from within the wetted area to represent the area with maximum root density. In the case of bedded groves, the sampling should be taken under the tree towards the bed top, since the soil disturbance is much greater towards the furrow side. Samples need to be air-dried, screened, and thoroughly mixed before analysis.

Soil and leaf tissue sampling guidelines, in citrus groves, are described by Obreza (1990). A brief description is as follows: Large groves should be partitioned into management units of not more than 8 hectares. A management unit represents similar soil series and scion/rootstock combination. For extremely large groves, where sampling each management unit is not feasible, an indicator block should be identified for decreasing the number of samples into manageable numbers. An indicator block is a designated zone, which represents a fairly uniform large grove. An aerial photo of the grove may be used to select the indicator block. These sampling guidelines help to minimize variability by grouping similar tree and soil types. Annual sampling may be taken at the same time recommended for tissue sampling, in an effort to reduce the number of trips across the field, and provide information for fall fertilization decisions. Once the indicator block or management unit is identified, it is recommended that soil sampling be taken from around 15-20 trees. One 15 cm deep core, about 2.5 cm in diameter, should be taken within the irrigated zone close to the drip line of each tree. The core should be placed into a plastic bucket and mixed with other cores from that unit or the sampling indicator block. The resulting composite sample should be air-dried prior to shipping to a soil-testing laboratory. Although most feeder roots are in the top 15 cm depth soil, it is recommended to take occasional deep soil samples at least down to 60 cm depth to evaluate the long-term trend of nutrient distribution in the soil profile. In the case of the under the tree micro sprinkler irrigation system, the wetted area generally represents the drip line of the tree canopy. Continuous injection, depending on the irrigation water quality, can affect the soil properties within the wetted area. It is advisable to sample in and out of the wetted area to make this comparison.

The analytical procedures used for soil analysis vary considerably from one laboratory to another. Research has developed suitable chemical extraction procedures for measuring the plant available nutrients in the soil. The common extracts used include either water, Mehlich 1 (double-acid), Mehlich 3, neutral ammonium acetate, ammonium acetate at pH = 4.8, and ionic exchange resin (Mehlich, 1953, 1978, 1984; Raij et al., 1986; Haby et al., 1990; Hanlon et al., 1995).

Soil Test Calibration and Critical Concentrations

Soil testing has been considered as an auxiliary or complimentary tool to plant analysis for recommendation of fertilizer for citrus production. Results of chemical analyses provide a basis to assess the nutrient reserve in the soil, and assist developing efficient fertilizer programs for optimal production. The calibration of soil test values, a critical step that links the soil extraction value with citrus production and quality, might differ for each extractant since different extractants measure different forms of plant available nutrients.

Chapman (1960) presented standards for starting a program of nutritional evaluation and fertilizer recommendation for citrus using leaf and soil analysis. The relationship between the soil-K content and citrus fruit yield have been fairly significant for Florida and California production conditions where excessive leaching occurs. Potassium availability is dependent on a number of other soil factors. Furthermore, citrus tree roots extend much deeper than the typical depth of soil sampling generally conducted for diagnostic purposes (Reitz and Koo, 1959; Koo, 1968; Jones et al., 1973; Obreza, 1990; Hanlon et al., 1995). In Florida citrus production region, due to the lack of soil test calibrations for citrus production, the soil test critical concentrations developed for other crops are used as standard guidelines for citrus. In most cases, however, plant analysis was used in conjunction with soil analysis data (Hanlon et al., 1995). The critical concentration ranges of P and K based on the soil extractions using Mehlich 1 and ammonium acetate (pH = 4.8) are shown in Tables 3 and 4.

Experiments conducted in South Africa demonstrated the importance of soil analysis for K to assist developing optimal citrus fertilization programs. Accordingly, Du Plessis (1977) concluded that good fruit yield response to applied K was possible in soils with exchangeable K < 2.5 mmol_c dm⁻³. In soils with exchangeable K > 6 mmol_c dm⁻³, applications of K did not increase yield or the quality. The author recommended the use of both soil and leaf analysis results to determine K

TABLE 3. Interpretation of soil analysis data for citrus using double acid (Mehlich-1) extractant.

Element	Very Low	Low	Medium	High	Very High
kg ha ⁻¹					
P	< 22	22-34	34-67	67-134	> 134
K	< 45	45-78	78-134	134-280	> 280

Source: Adapted from Tucker et al. (1995).

TABLE 4. Interpretation of soil analysis data for citrus using ammonium acetate (pH = 4.8) extractant.

Soil Texture	Element	Rating		
		Low	Medium	High
kg ha ⁻¹				
Organic	P	< 10	10-20	> 20
Sandy	P	< 8	8-17	> 17
Loamy sands	P	< 4	4-10	> 10
Sandy loams	P	< 2	2-4	> 4
Organic	K	< 140	140-280	> 280
Mineral soils	K	< 85	85-140	> 140

Source: Adapted from Tucker et al. (1995).

requirement of citrus trees to improve the accuracy of the K fertilizer recommendation.

Jorgensen and Price (1978) recommended the use of ammonium acetate extraction for evaluation of soil-K status and developing optimal K fertilization program. This approach showed to be an effective method for determining fertilizer needs. Similarly, soil testing for K has been used also in Spain as a guide for application of fertilizer to citrus orchards (Legaz and Primo Millo, 1985).

Studies conducted in Brazil, where citrus production is on low-lying soils with very little contribution of non-exchangeable forms of K, demonstrated that soil testing for K using an ion-exchange resin extraction (Raij et al., 1986) was important to determine the K requirement for citrus trees. This technique is supported by significant relationships observed between fruit yield of sweet orange or lemon trees and exchangeable soil-K data from long-term trials in different locations (Cantarella et al., 1992; Quaggio et al., 1996). Based on these results, soil-K analyses have proven to be a useful tool to evaluate the K availability status for citrus production in Brazil and to develop K fertilization programs.

Quaggio et al. (1998) showed a reciprocal linear relationship between relative fruit yield of citrus and exchangeable K in the soil. The measurement of soil K was using anion resin exchange method (Raij et al., 1986). The optimal exchangeable soil K was $2.0 \text{ mmol}_c \text{ dm}^{-3}$ (Figure 1). This value is lower than that reported by Hunziker (1960) in Florida, that is, $2.9 \text{ mmol}_c \text{ dm}^{-3}$. The response function developed for citrus showed considerable similarity to those of annual crops reported from long-term studies conducted in Brazil (Cantarella et al., 1998; Quaggio et al., 1998). Using results of soil-K test calibration with citrus yield response, soil K critical levels were established as follows (in $\text{mmol}_c \text{ dm}^{-3}$) 0.8 = Very low; 0.8-1.5 = Low; 1.6-3.0 = Medium; and >3.0 = High (Figure 1). Accordingly, an increase in fruit yield was appreciable in soils with K content in the low or very low exchangeable K status (Figure 2). On the contrary, in soils with exchangeable K in the medium to high range, no further fruit yield increase was observed. A recent study in Brazil demonstrated significant correlations of applied K rates with either soil test K ($R^2 = 0.73$), fruit yield ($R^2 = 0.74$), or average leaf K content ($R^2 = 0.84$) for 4- to 5-year-old 'Pera' sweet orange trees (Mattos Jr., 2000). Maximum fruit yield was observed at soil exchangeable K level of $2.0 \text{ mmol}_c \text{ dm}^{-3}$, and 13 g kg^{-1} K in the spring flush leaves collected from fruiting terminals.

Leaf Sampling and Analysis

Sampling guidelines described under the "Soil Sampling" section are applicable for leaf sampling. Leaf tissue sampling is a valuable tool for diagnosis of tree nutritional disorders and can also serve as a monitoring

FIGURE 1. Relative fruit yield of citrus as a function of soil exchangeable potassium. Data were pooled from 6 experiments conducted using 4- to 7-year-old trees (Adapted from Quaggio et al., 1998).

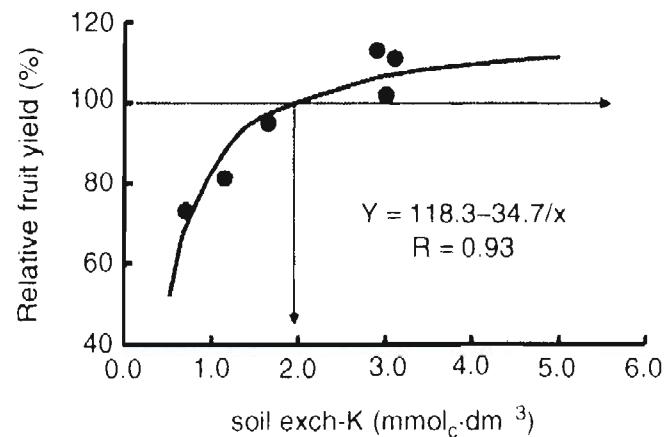
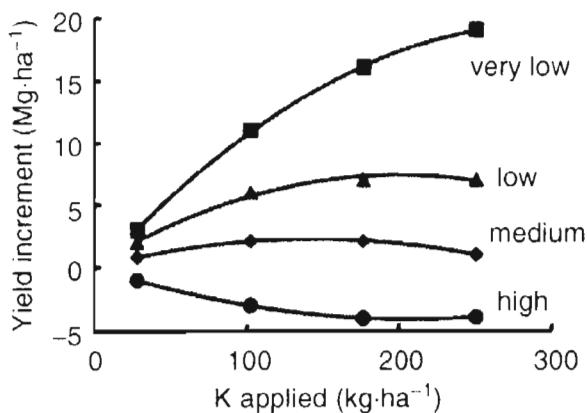


FIGURE 2. Citrus fruit yield response to various K levels in soils with varying native status of exchangeable K. Data were pooled from 6 experiments conducted using 4- to 7-year-old trees (Adapted from Quaggio et al., 1998).



tool for evaluation of growth and yield. This provides an important basis to adjust the K fertilization to overcome deficiencies and/or avoid its excessive application. The Florida recommendations suggest using 6-month-old spring flush leaves sampled from non-fruiting terminals for monitoring the tree nutritional status (Tucker et al., 1995). Leaf samples collected on an annual basis will provide information about nutritional trends with time. The sample must represent the portion of the grove from which it was collected. This source of error can be minimized by grouping like areas of variety, tree age, and soil into units of the grove, which will receive the same management regime.

A representative sample consists of at least 100 leaves, or about 8-10 leaves per tree. The age of the leaf influences the concentration of mineral elements. The concentrations of most macronutrients remain stable between 4 and 6 months following leaf emergence (Smith, 1966). Therefore, this stage of growth should be chosen for sampling the leaves for evaluation of mineral contents. The critical limits of various mineral elements, which are summarized by Tucker et al. (1995), are based on the analysis of leaves at this maturity stage. Annual sampling from an indicator block is recommended during July through September. Soil sampling is also recommended from around the same trees that were used for leaf sampling. Leaves that have been recently sprayed with fungicides or nutritional solutions should not be sampled for micronutrient analysis due to the difficulty of surface decontamination of micronutrients sprayed on the leaves by the routine leaf-washing

method (Alva and Tucker, 1998). The leaf samples have to be washed prior to analysis to remove soil and dust particles.

Leaf samples are generally taken randomly from 15 to 20 trees within the management unit (or indicator block). The past research has provided the basis to recommend an appropriate stage of leaf growth as representative of the tree nutritional status. Accordingly, past research has shown the use of 4- to 6-month-old spring flush leaves from the non-fruiting twigs as the appropriate physiological sampling for diagnosis of nutritional status of the trees. This sampling technique was originally proposed by Einbleton et al. (1963) for California citrus nutrient management. This method was also recommended for Florida (Obreza et al., 1996), Texas (Swietlik, 1996), and Australia (Gallasch, 1996) citrus nutrient managements.

Based on the research conducted in South Africa, DuPlessis and Koen (1996) recommended spring flush sampling from the fruiting terminals. This recommendation is also followed in Brazil (Quaggio et al., 1996). Khan et al. (1992, 2000) examined the relationship between the nutrient status of orange leaves sampled from fruiting and non-fruiting terminals. They reported a significant difference in 10 of the 12 elements being analyzed in the leaves sampled from fruiting versus non-fruiting terminals. However, critical nutrient concentration limits are being developed separately for the leaves sampled from the fruiting versus non-fruiting terminals as described in the next section.

Interpretation of Leaf Test Results

Tucker et al. (1995) summarized the critical concentration ranges of various nutrients in 4- to 6-month-old spring flush leaves (from non-fruiting terminal) of citrus trees. The most generally accepted standards of K critical levels in leaves are as follows (Tucker et al., 1995; Calvert, 1969; Hunziker, 1960; Reitz and Koo, 1959) (in g kg⁻¹ on dry weight basis): less than 7 = Deficient; 7-11 = Low; 12-17 = Optimum; 18-24 = High; greater than 24 = Excess. If annual testing results are found to be in the deficient or low categories, an increase in annual fertilization of that nutrient is recommended in quantities proportional to the degree of deficiency. Alternately, if annual results fall within the high or excessive ranges, the annual fertilization rate of that nutrient should be adjusted downward. If a change in fertilization is indicated, the adjustment should be reasonable. The intent is to find the correct nutrient management that maintains leaf tissue in the optimum range, but does not lead to over fertilization and possible adverse environmental and economic

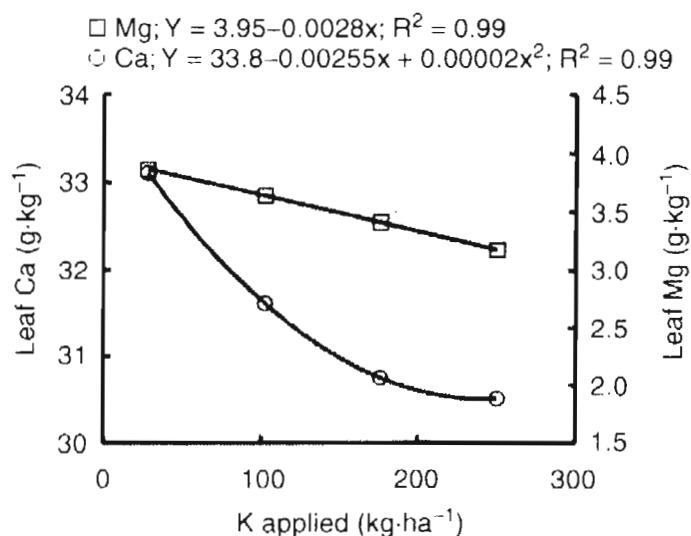
impacts. The critical K concentration limits followed in Brazil (Quaggio et al., 1996) for the leaf samples taken from fruiting terminals are (g kg^{-1}): Ow = < 9; Adequate = 10-15; Excessive = > 20.

POTASSIUM EFFECTS ON FRUIT YIELD AND QUALITY

Field experiments have demonstrated the positive effect of K fertilization on fruit yield of citrus trees grown in soils with low levels of available K as discussed below. On the other hand, fruit yield may be significantly reduced with excess K supply. An experiment conducted in a commercial grove with 6-year-old 'Murrcott' tangor trees on 'Rangpur' lime planted in a sandy loam Oxisol showed that fruit yield (average for six harvests) was reduced by 53% with an increase in K application from 25 to 225 kg ha^{-1} (Mattos Jr. et al., 2004). Trees that received the highest K rate showed severe defoliation, and decreased calcium and magnesium contents in the spring flush leaves sampled from the fruiting terminals (Figure 3).

Fruit size or fruit mass and peel thickness appear to be the most affected fruit traits with varying K availability in citrus groves (Hearn, 1993; Jackson, 1991; Wutscher and Smith, 1993; Davies and Albrigo, 1994). Deszyck et al. (1958) demonstrated an increase in fruit size and grade with application of mixed fertilizer containing 0-16% K. Fruit weight of 'Hamlin' and 'Valencia' cultivars, respectively, increased

FIGURE 3. Calcium and magnesium concentrations in leaves of 'Murrcott' trees six years after yearly application of K rates to the grove planted on a sandy loam Oxisol (Adapted from Mattos et al., 2004).



from 162 to 184 g, and 179 to 247 g per fruit with the above increase in K applications. Juice acidity (a characteristic defined by the content of soluble acid compounds, of which 85-90 % is present as citric acid) and total soluble solids content (TSS) of juice (defined basically by 50/50 mixture of sucrose and glucose + fructose; (Reed et al., 1986) may also change with varying rates of K. In addition to these effects, Sites and Deszyck (1953) have shown that K fertilization increases vitamin C content in the juice. Table 5 shows other effects of K on fruit quality (Koo, 1988).

Although it is generally believed that high rates of K fertilization will induce greater cold hardiness in trees, this was not supported based on the observations in Florida following the 1957 and 1962 freezes. Smith and Rasmussen (1958) found that trees high in K appeared to be more susceptible to freeze injury than those with moderate levels of K fertilization.

Orange Cultivars

Reese and Koo (1974, 1975) conducted a long-term study to evaluate the effects of N and K rates on 'Hamlin', 'Pineapple', and 'Valencia' orange trees on 'Rough lemon' rootstock grown in a well-drained Astatula

TABLE 5. Effects of mineral nutrition and irrigation on quality of citrus fruits.

Characteristics ¹	Elements				
	N	P	K	Mg	Irrigation
Juice Quality					
Juice content	+	0	-	0	+
Soluble solids (SS)	+	0	-	+	-
Acid (A)	+	-	+	0	-
SS/A ratio	-	+	-	+	+
Juice color	+	0	-	?	0
Solids/box ²	+	0	-	+	-
Solids/ha	+	+	+	+	-
External Fruit Quality					
Size	-	0	+	+	+
Weight	-	0	+	+	+
Green fruit	+	+	+	0	+
Peel thickness ³	3	-	+	-	-

¹ Increase (+), Decrease (-), No Change (0), No Information (?); Adapted from Koo (1988).

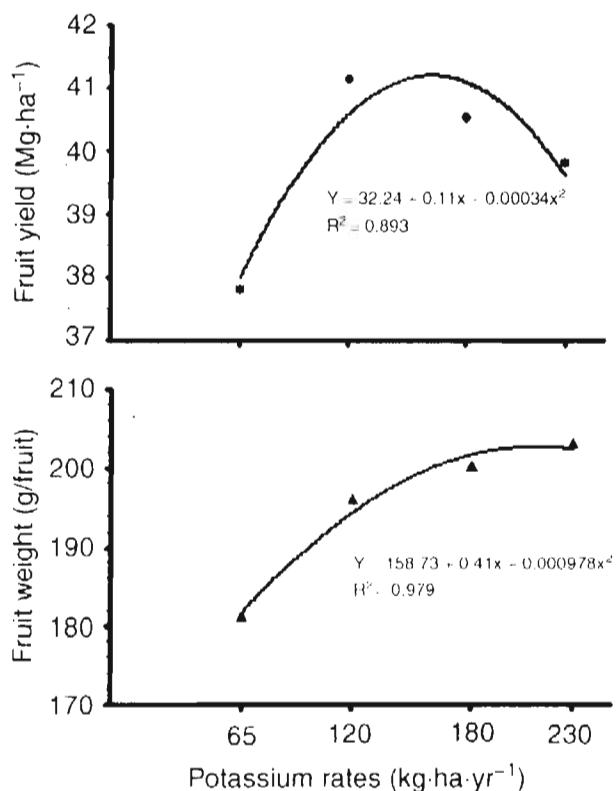
² box = 40.8 kg.

³ Except in young trees where peel may be thicker.

fine sand. Mean fruit yields over 3 years, beginning with 11-year-old trees, and across three cultivars with K applications at 65, 120, 180, and 230 kg ha⁻¹ yr⁻¹ rates are shown in Figure 4. The corresponding increase in fruit size was 181-196 g per fruit. Further increase in K rates to 180 and 230 kg ha⁻¹ had no effect on the fruit yields or fruit size. The fruit diameter increased significantly with an increase in K rate from 65 to 120 kg ha⁻¹. Further increases in K rates to 180 and 230 kg ha⁻¹ showed only rather marginal increase in fruit size. Juice acidity was 0.70, 0.73, 0.75, and 0.75 percent at K rates of 65, 120, 180, and 230 kg ha⁻¹ rates, respectively. All other internal and external fruit quality parameters had no significant effects of K rates during the course of the 6-year study.

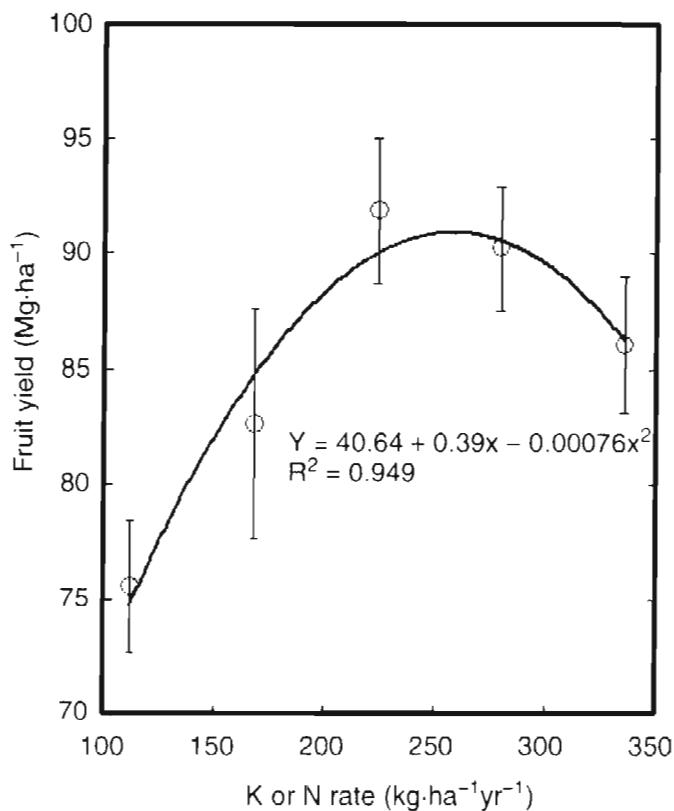
A long-term (six years, 1993 through 1998) fertilizer response study was conducted in Highlands County, Florida, using 25 + year-old 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock (Alva and Paramasivam, 1998b; Paramasivam et al., 2001). The rates of N, P, and K were varied simultaneously by application of various rates of N:P:K

FIGURE 4. Fruit yield and fruit weight response to various rates of potassium of 11-year-old orange trees. Three years mean across 'Valencia', 'Hamlin', and 'Pineapple' cultivars, all on 'Rough lemon' rootstock (Adapted from Reese and Koo, 1974, 1975).



blend at 6.0:1.0:6.1 ratio. This experimental approach was chosen due to the importance of maintaining a fixed ratio of N:P:K rather than varying single nutrients at a time. The N or K rates evaluated were 112, 168, 224, 280, and 336 kg ha⁻¹ yr⁻¹ using water soluble granular sources, that is, ammonium nitrate and muriate of potash as N and K sources, respectively. The annual fertilizer rate was delivered in four split doses with three applications during February through May, while the fourth application was in September-October. The mean fruit yield response for 1995 through 1998 is shown in Figure 5. Under the conditions of this experiment (i.e., simultaneously varying N, P, and K rates and with optimal irrigation scheduling), maximum fruit yield of about 90 Mg ha⁻¹ yr⁻¹ was obtained with about 250 kg ha⁻¹ yr⁻¹ of K. It is important to underscore that this long-term experiment was conducted on a highly productive commercial grove, which was managed as per the industry production

FIGURE 5. Fruit yield response of 23+ year-old 'Hamlin' orange trees on 'Cleopatra mandarin' rootstock (mean yields across 1995 through 1998) as a function of different rates of N and K as water soluble granular fertilizer applied in four split doses per year (A. K. Alva, 2005, unpublished data). Vertical line across each data point represents standard error of mean.



management program. The mean yields reported represent almost two-fold of the Florida mean yields. Thus, the optimal K rate observed in this study is applicable across the state under different management systems.

Quaggio et al. (2000) established N, P, and K rates for optimum yield and superior fruit quality of 'Valencia' and 'Pêra' sweet oranges grown in non-irrigated groves during four harvests. The experiments received four K rates (24, 91, 158, and 225 kg ha⁻¹ yr⁻¹) applied on the soil surface. Fruit yield response of both orange cultivars to K fertilization was dependent on nutrient availability in the soil. Fruit size increased with an increase in K rate over the entire range of K rates evaluated in this study. Soluble solids per box of fruit were negatively correlated with leaf K concentration. Results of soil and leaf analyses calibration obtained in this study have been used for establishing guidelines for orange fertilization in Brazil, depending on the fruit production either for fresh fruit market or juice market.

Grapefruit

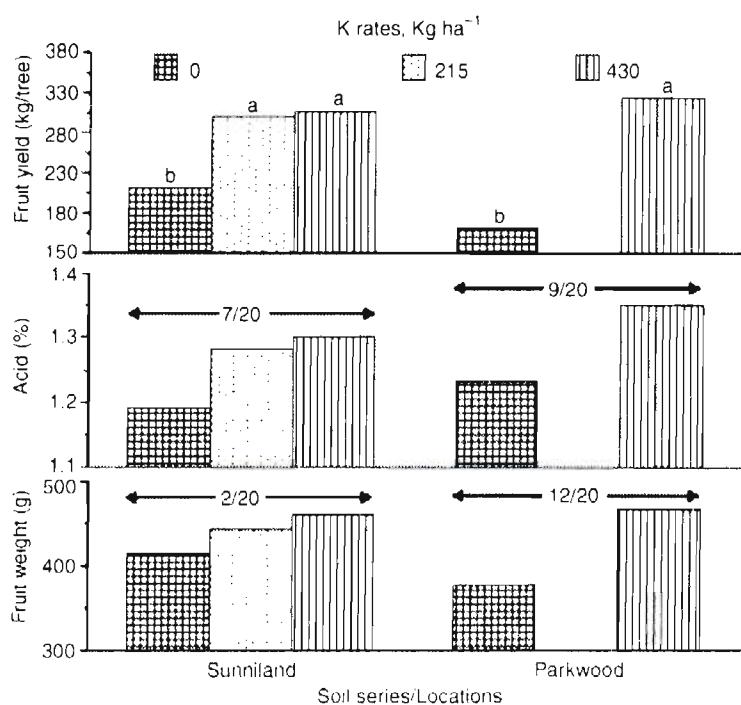
A 20-year-long field experiment was conducted by Calvert (1973) using 'Marsh' grapefruit trees grown in a Sunniland fine sand as well as Parkwood loamy fine sand. The trees were 23 years old when the study began. The K treatments included either 0, 1.5, or 3.0 kg per tree per year (equivalent to 0, 215, or 430 kg ha⁻¹ yr⁻¹) in Sunniland soil, and 0 and 3.0 kg per tree per year in the Parkwood sand. The fruit yield response to K rate was non-significant in both soils during the first 10 years of the study. The mean fruit yields per tree during the first 10 years of the study were 350 and 348 kg for the trees that received 1.5 and 3.0 kg K per tree, respectively, compared with 323 kg fruits per tree for those that received no K in the Sunniland fine sand site (data not reproduced in this review). In the Parkwood sand site, the mean fruit yields were 290 and 327 kg per tree for the zero K and 3.0 kg per tree treatments. Significant response to K fertilization was obtained in the subsequent 10 year duration of the study. The mean fruit yield increased to 301 kg per tree with application of 1.5 kg K per tree per year, compared with 219 kg fruit per tree for those receiving no K in the Sunniland fine sand (Figure 6). Further increase in K rate to 3.0 kg per tree had no significant effects on the mean fruit yield compared with that of trees receiving 1.5 kg per tree. In the Parkwood fine sand, the mean fruit yield increased to 325 kg per tree with application of 3.0 kg K per tree compared with 171 kg per tree with no K application for 20 years during the course of the study.

The most noticeable response to K fertilization was an increase in juice acidity (significant during the 7th and 9th years out of 20 years at the two sites), and fruit weight (12 out of 20 years at one site). The fruit weight increased from 414 to 460, and from 377 to 466 g per fruit with an increase in K rate from 0 to 3.0 kg per trees in the two soils (Figure 6).

Lemons and Persian Lime

Early work of Koo (1963) showed that K requirement for lemon was greater than that for orange. Koo (1963) suggested that for attaining optimal lemon yields, K application rates must be 25% greater than that of the N rate. Koo et al. (1973, 1974) conducted an N × K factorial experiment with young bearing lemon trees grown on a Florida sandy soil during

FIGURE 6. Effects of potassium rates on fruit yield, fruit weight, and juice acid content of white 'Marsh' grapefruit trees in two soils (Adapted from Calvert, 1973). Fruit yield (mean of 1961-1970 years' response; during 1951-1960 only 2 years fruit yield response was significant. Means followed by similar letters for fruit yield by location are not significantly different at $P = 0.01$). For juice acidity and fruit weight data, the fraction shown on top of the set of histogram by each location indicates the number of years the treatment effects were significant out of 20-year duration of the study (1951-1970).



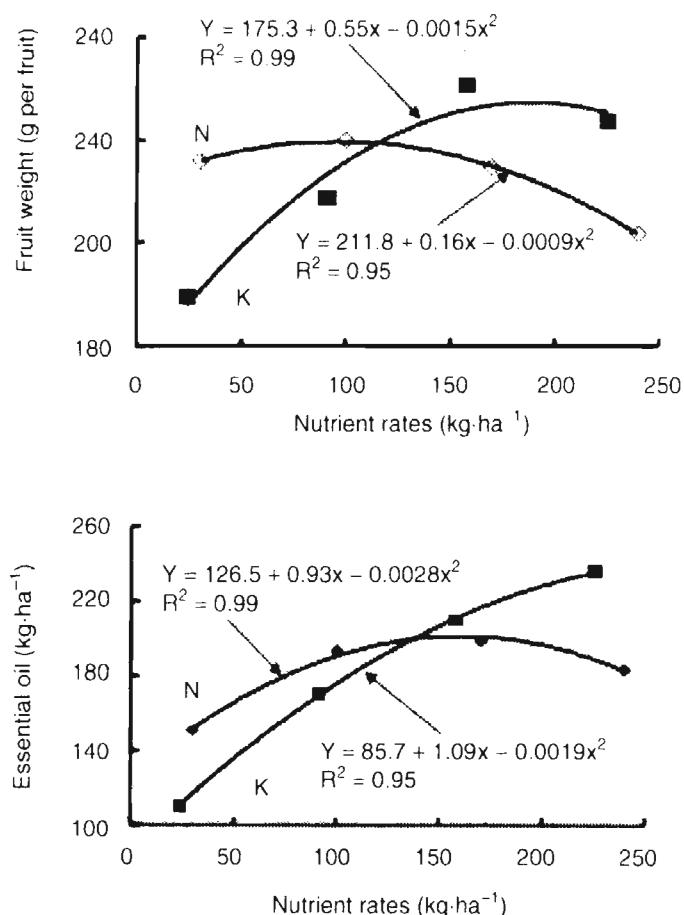
four seasons. The N rates significantly affected fruit quality as evidenced by decreased fruit size and acid content in the juice, and increased peel oil and percentage of green fruits. The higher N rates accounted for lower marketable production. Potassium had no significant effect on fruit yield, but increased juice acid content. The highest lemon yield was 28 Mg ha^{-1} (average of four harvests), which is considered low for this citrus variety and might explain the absence of response to K fertilization. Since high acidity is preferred for lemon and lime, application of more K is beneficial to increase the acid content. Embleton et al. (1964) and Koo (1963) have shown a 15% increase in acid content of lemon with application of high K compared with that with low K fertilization.

In South Africa, lemon response to N, P, and K fertilization was studied by Du Plessis et al. (1975) and the results showed that higher yields were obtained with N and K rates of 160 and 150 kg ha^{-1} , respectively. No response was observed for P rates. Optimal yields were associated with leaf nutrient contents of N = 23, P = 1.1, and K = 9.0 g kg^{-1} . The optimal leaf K value recommended by DuPlessis et al. (1975) was lower than that proposed by Koo et al. (1974).

A field trial with 'Sicilian lemon' on 'Volkameriana' rootstock was carried out for 7 years in a low fertility sandy Oxisol (Quaggio et al., 2002). The grove received annual application of fertilizer mixtures at the following rates: N (30, 100, 170, and 240 kg ha^{-1}), P (9, 27, 62, and 79 kg ha^{-1}), and K (24, 91, 158, and 225 kg ha^{-1}). The maximum fruit yield, averaged for six harvests, was attained with N, P, and K rates of 220, 20, 310 kg ha^{-1} , respectively. The concentrations of N, P, and K in the leaves (sampled from the fruiting terminals) for the above treatments were 15-20, 1.8-2.2, 15-20 g kg^{-1} , respectively. Increasing K rates increased fruit size by 37%, and total production of essential oil to 100% (Figure 7). Results also demonstrated that monitoring leaf K concentration in response to increasing K rates was as sensitive as monitoring soil-K concentration to determine potassium availability in the soil to lemon trees. Maximum lemon yield was attained at leaf K $\sim 16 \text{ g kg}^{-1}$. This K concentration is much greater than the optimal leaf K for oranges, confirming a greater K requirement for lemon compared with that for oranges.

Young and Koo (1967) conducted a 3-year study on 10-year-old 'Persian' lime trees on 'Rough lemon' rootstock, grown in Lakeland fine sand. Potassium was applied at either 95, 190, or $320 \text{ kg ha}^{-1} \text{ yr}^{-1}$. In the third year of the experiment, fruit yield increased significantly from 362 to 436 kg per tree with an increase in K rate from 95 to 320 kg ha^{-1} . Fruit quality parameters including fruit diameter, fruit weight, peel thickness, soluble solids, juice and acid contents, showed no re-

FIGURE 7. Effects of nitrogen and potassium rates on fruit weight, and total oil production of lemon (Adapted from Quaggio et al., 2002).



sponse to K rate. The average leaf K concentrations over 3 years were 11.4, 14.3, and 15.4 g kg⁻¹ for the three K rates.

POTASSIUM EFFECTS ON POSTHARVEST QUALITY

Fruit Size

Large fruit is desirable for the fresh fruit market. The economic returns from large size fruit are significantly greater than that from medium or small size fruit. Therefore, management practices that improve fruit size has been an active area of research for a number of years. Early research has shown evidence of varying effects of 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) ef-

fects on increasing fruit size (Stewart and Parker, 1954; Hield et al., 1964; Monselise, 1979). The role of K on the fruit size has been summarized by Embleton et al. (1975) and DuPlessis and Koen (1988). Erner et al. (1993) reported that fruit size of 'Shamouti' and 'Valencia' oranges increased by 8 to 25% by spraying the trees with 20 ppm 2, 4-D plus 5% KNO_3 compared with that of the fruit from unsprayed trees. Their study also showed that spray application of 2, 4-D plus KNO_3 6-8 weeks after flowering (i.e., end of May or early June) gave the best response. Single application of the above spray was better than 2-3 applications for 'Shamouti' oranges, while the best response of 'Valencia' oranges was evident with 3 sprays per year.

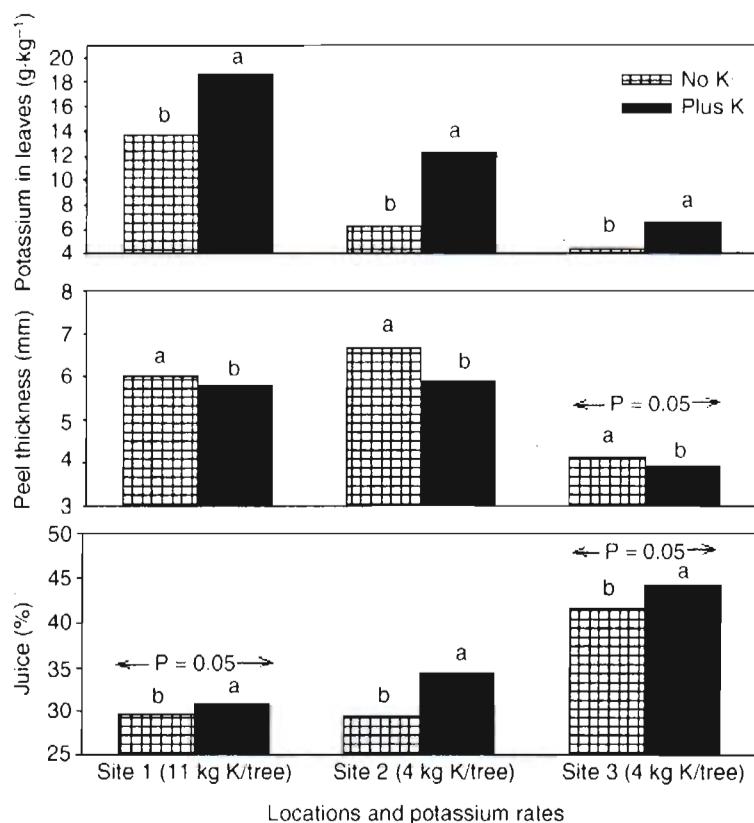
Peel Thickness

Increased rate of K applied to orange and grapefruit trees generally increased peel thickness of the fruit and decreased the juice content (Smith, 1963). Although the effects of K on lemons were not investigated until the 1960s, it was generally assumed that K effects on lemons would be similar to those on oranges and grapefruits. Embleton and Jones (1966) showed, for the first time, that in the case of lemons, increasing application of K (4-11 kg per tree) decreased peel thickness and increased juice acid content (Figure 8). They reported 18.7 g kg^{-1} leaf K concentration in site 1 with 11 kg per tree K application as compared with 13.7 g kg^{-1} K in the leaves of the trees, which received no K. In sites 2 and 3 leaf K concentrations were 6.2 and 4.4 g kg^{-1} , respectively, with no K but increased to 12.3 and 6.6 g kg^{-1} , respectively, with application of 4 kg K per tree. The peel thickness marginally decreased, while the juice content slightly increased in fruits produced from trees that received K application compared with those of the trees without K at all three sites.

Peel Disorders

Research has confirmed that K nutrition greatly influences fruit external quality characteristics such as fruit size, color, peel thickness, and incidence of peel disorders (Bar-Akiva, 1977; Rodriguez et al., 2000; Quaggio et al., 2002). Several rind disorders of orange and mandarins are associated with low K. Potassium nutrition influences the rind thickness and texture of fruits; therefore, reduced K availability will predispose the fruits for various disorders. Albrigo (1978) reported several peel blemishes and disorders in citrus fruit caused by pathogens and/or

FIGURE 8. Effects of potassium on the concentration of potassium in the leaves as well as peel thickness of 'Valencia' orange fruits and percent juice in three location trials (Adapted from Embleton and Jones, 1966). Means followed by similar letters, within each site and each response parameter, are not significantly different according to Duncan Multiple Range Test. Mean separation was significant at $P = 0.01$, except those which are shown as $P = 0.05$.



nutritional factors. Among these causes, K nutrition plays a key role in the development of many peel disorders. Creasing is a pre-harvest peel disorder observed in major citrus production areas in Florida, California, Australia, and South Africa. Generally, creasing results from the cavities that form in albedo in the final stages of ripening. The exact cause of creasing is not known, but the incidence of creasing increases with increased peel turgidity at harvesting time and is particularly high if fruits are harvested after a heavy rainfall. Potassium plays a key physiological role in influencing the fruit internal water turgor. This, in turn, explains the role of K on the incidence and severity of fruit creasing. Grierson (1965) reported that K influenced the occurrence of creasing in 'Valencia' oranges in Florida. Studies conducted in Florida (Sites and Deszyck, 1953) and in South Africa (Fourie and Joubert, 1957)

have also shown increased creasing and poor storage of fruits, which received low K levels. Jones et al. (1967) observed a reduction in creasing following an increase in K fertilization. Knorr (1973) also reported reduced incidence of fruit creasing when trees received increased levels of K applied either on the soil or on the foliage. Recent studies from California indicate a relationship between rind thickness, K content, and creasing development. Accordingly, rind thickness and K concentration in the peel accounted for 65% of variation in creasing in 'Navel' and 'Valencia' oranges (Treeby et al., 2003). Studies in South Africa also showed the effects of K, as well as other nutrients including P, B, Ca, Mn, and S, on the incidence of creasing (Bower, 2003).

Fruit splitting is believed to be a function of water turgidity and peel thickness. It is particularly severe on the fruit from young trees. Fruit splitting in citrus is a disorder similar to creasing, and both are significantly influenced by K fertilization in citrus. The incidence of fruit splitting is greater under K deficient conditions (Koo, 1961). Bar Akiva (1977) demonstrated that splitting of 'Valencia' orange fruits disappeared in trees that received adequate K fertilization compared with 23% of the fruits with splitting problem in the trees that received no K fertilization.

Rumple is a pre-harvest peel disorder characterized by collapse of the rind between the oil glands. This disorder generally begins at the time of colorbreak (Knorr, 1973), and is severe in lemons grown in Florida. There have been some indications that high K tends to decrease the proportion of fruit with rumple. Similar to other nutrition studies in Florida, high K and low N reduced the incidence of rumple (Knorr, 1973).

Stem end rind breakdown (SERB) is a general term given to fruit with a collapsed peel at the stem end. SERB incidence in South Africa was reportedly triggered by K and B deficiency. Grierson (1965) also reported that SERB was associated with the deficiency of K. Reitz and Koo (1960) reported that SERB was most abundant in fruit from trees that received high N and low K rates, while increased K rates decreased SERB. Grierson (1986) reported that SERB incidence was greater in small, thin-skinned fruit grown under water stress. There is considerable evidence to support that K and other micronutrients play a role in SERB incidence.

Postharvest pitting, a newly defined physiological peel disorder, is caused by high temperature storage of waxed fruit (Petracek et al., 1998; Petracek and Dou, 1998). This disorder is of considerable importance because it can cause substantial losses of fruits during storage of waxed fruits. Pitting is visually characterized by the collapse of oil glands and may develop within the first week of storage at higher temperatures (Petracek et al., 1998). The effects of K and irrigation on pitting incidence

of 'White Marsh' grapefruit have been evaluated in a 3-year field study (Dou et al., 2000). High N and K decreased the incidence of pitting (Figure 9). In the fruits sampled in November, the incidence of pitting increased with increased duration of storage across all nutrition treatments. The storage duration effect was negligible on later harvested fruits, that is, January. In a parallel factorial experiment with N and K on 'White Marsh' grapefruit trees, increasing K levels in the range of 70-420 kg K ha^{-1} decreased the percentage of pitting at 168 and 336 kg ha^{-1} N rates (data not presented). Increasing the duration of storage from 3 to 5 weeks increased the percentage of pitting. The concentration of K in the peel increased with an increase in K rates at both N rates (Figure 10). Grierson (1965) reported that the pattern of response was similar to that of SERB. The concentration of K in albedo was greater in pitted areas than in non-pitted areas of pitted fruits. Tamin et al. (2003) reported that fruit with superficial rind pitting have lower rind K concentration than healthy fruit.

Mauk and Dimitman (1998) stated that the concentrations of N, P, and K were lower in pitted fruit as compared with those in the non-pit-

FIGURE 9. Effects of nitrogen and potassium rates on percent pitting of 'White Marsh' grapefruits sampled at different times and stored over three or five weeks (H. Dou 2005; unpublished data). Means followed by similar letters, within each sampling date and storage duration, are not significantly different according to Duncan Multiple Range Test at $P = 0.05$. NS = non-significant.

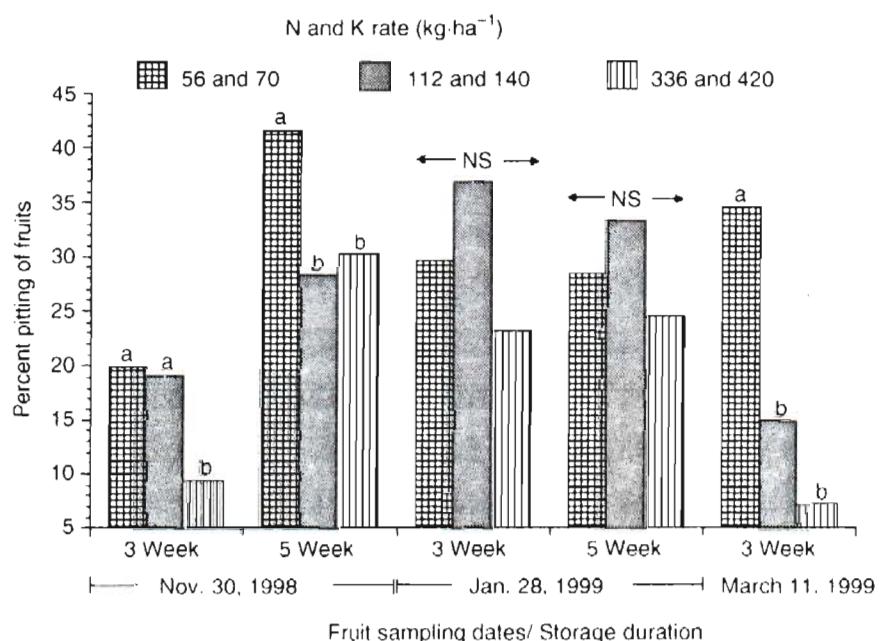
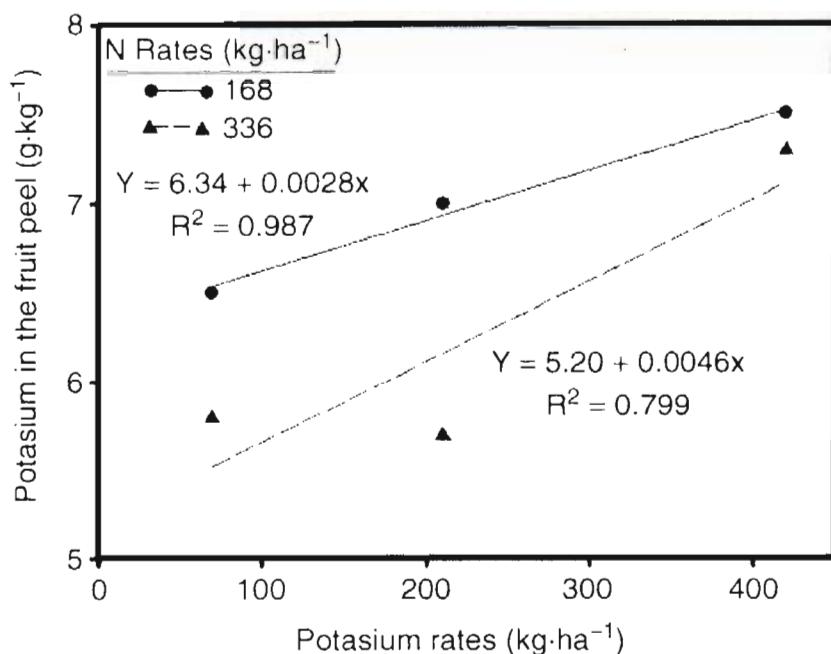


FIGURE 10. Effects of increasing rates of potassium at two different rates of nitrogen on potassium concentration in the peel of 'White Marsh' grapefruits (H. Dou 2005, unpublished data).



ted fruits. Tamin et al. (2003) reported that spraying K on the tree foliage reduced the incidence of pitting with 'Shamouti' oranges in Israel. The authors concluded that K deficiency led to malfunction of bio-membranes, which caused water loss followed by cell collapse and superficial rind pitting. Ait-Oubahou et al. (2003) reported peel pitting of 'Fortune mandarin' fruit was slightly reduced by foliar application of fertilizers containing Ca and K, 4-8 weeks before harvest. In summary, K nutrition of the trees influences most of the above physiological fruit disorders. The optimal K fertilization rate and postharvest management, that is, storage conditions, must be maintained to minimize the above peel disorders.

GUIDELINES FOR POTASSIUM FERTILIZATION

Non-Bearing Trees

Management of young trees requires maintaining adequate nutrition and irrigation, and minimizing adverse effects of weeds, diseases, pests, and freeze damage. Optimal growth requires balanced and optimal lev-

els of nutrients and irrigation. However, excesses of any inputs are nonproductive, costly, and may result in loss of soluble nutrients, including K, by leaching and/or runoff.

Experiments to investigate the fertilizer requirement of non-bearing trees have been very few. The fertilizer recommendations developed are for orange trees, however, those recommendations are also adapted for other citrus varieties due to the lack of adequate research-based information on the latter. Table 6 shows K rate recommendations for non-bearing citrus trees in Florida during the first three years (Tucker et al., 1995). These fertilizer guidelines include a range of rates for each tree age because a number of factors influence fertilizer requirements. Criteria for selecting a rate within the recommended range include history of fertilization in the tree nursery, soil type, land history, and fertilizer placement. Increased frequency of fertilizer application, and better timing and placement to avoid rainy periods improve the nutrient uptake efficiency. The application rate of a nutrient is a function of nutrient requirement and nutrient uptake efficiency. Increased nutrient uptake efficiency contributes to decrease in rate of application.

Responses of various scion/rootstock combinations to varying rates of different nutrients are not extensively investigated. Results of a network of field experiments have suggested that the response of orange cultivars to phosphorus (P) fertilization is greater for trees on 'Cleopatra mandarin' compared with either 'Swingle citrumelo' or 'Rangpur lime' (Mattos Jr., 2000). Likewise, the response of young bearing orange trees to K is more significant for trees grafted on 'Swingle citrumelo' rootstock compared with that of trees on 'Rangpur lime' rootstock. Fine tuning of fertilizer recommendations for citrus will need to take into account such differential response of scion and rootstock combinations.

Recommendations by Tucker et al. (1995) indicate that the fertilizer blend for young trees planted on previously uncropped soils should contain the following ratio of elements: N-1, P₂O₅-1, K₂O-1, Mg-1/5, Mn-1/20, Cu-1/40, and B-1/300, until such time when the soil and/or leaf analysis, and tree appearance indicate that one or more of nutrients

TABLE 6. Recommended K rates for nonbearing citrus trees in Florida.

Year in Grove	g K tree ⁻¹ yr ⁻¹ (range)
1	120-240
2	240-480
3	370-740

Source: Adapted from Tucker et al. (1995).

may be omitted and/or applied at reduced rates. On previously cropped soils the proportion of P in the blend may be reduced or omitted if soil-test results indicate sufficient residual P. Liquid and dry fertilizer sources are equally effective for young tree growth and have the same approximate formulations.

Tucker et al. (1995) recommendations also suggest that fertilizer applications in a number of small doses generally increase nutrient uptake efficacy by providing available nutrients within the root zone over prolonged growing period and by reducing leaching that can occur due to excess rainfall and/or irrigation. Dry fertilizer may be applied in 4-6 doses during the annual growing period, while the liquid source could be split in 10-30 applications. Cost of injection of liquid fertilizer source during irrigation is relatively small for many systems if fertilizer injection can be automated. Due to the slow release characteristics of nutrients in controlled-release fertilizers (CRF), this source can be applied at reduced frequency decreasing the application cost. Controlled-release formulations may be applied as a pre-plant treatment, incorporated after planting, or broadcast to insure uniform distribution of nutrients throughout the enlarging root zone of young trees.

Irrigation management of young trees is critical because soil moisture could deplete rapidly particularly in sandy soils. Citrus trees are quite sensitive to water stress. In the case of fertigation (i.e., delivery of nutrients through irrigation), water and fertilizer placement, as well as frequency of application are managed more efficiently compared with a dry fertilization program. This application technique, in turn, could result in better growth of the trees under fertigation compared with that under dry fertilization program. Excess irrigation is particularly detrimental under fertigation. Small wetting areas of the emitters used for small trees provide high application rate on unit surface area. The duration of irrigation during fertigation, as well as flush time to clean the lines following delivery of nutrients should be relatively short to avoid excess water drainage below the root zone, which can contribute to leaching of water and nutrients below the root zone.

Trees in replanted areas and individual resets in mature groves should also receive recommended fertilizer rates according to tree age. Depending on the grove age, resets may not grow well if they only receive fertilizer during mature tree application because only a small amount of material may be deposited in the young tree root zone. Because the mature tree fertilizer is spread over a large portion of the grove area both in the case of dry granular form or liquid source used for fertigation, the area of fertilizer application for mature tree grove repre-

sents considerably greater area per tree as compared with the restricted rooting area of the young trees. This situation can be overcome by application of CRF for the resets in a mature grove. CRF can be applied once a year due to its slow release characteristics, which provides a continuous release of available nutrients over a prolonged period without nutrient losses by leaching.

Bearing Trees

Recommended K rates in Florida (Tucker et al., 1995) for bearing orange, grapefruit, and other citrus varieties and frequency of application of dry granular form and fertigation are shown in Table 7. Managing fertilization for improved fruit quality is important for both processed and fresh fruit markets although increasing tree growth continues to be an objective for several years after fruit production begins. When trees reach containment size, further canopy expansion is not desired and nutrition levels may be stabilized and possibly reduced. Nitrogen continues to be the most important nutrient element in overall fertilizer management. Other nutrients, especially K, have substantial effects on fruit production and fruit quality. Removal of elements by harvesting the crop becomes significant, but accounts for only part of the fertilizer requirements. Efficient management of irrigation continues to be critical. When using under-the-tree sprinklers, with one emitter per tree, the emitter-wetting pattern should increase with growth of the tree to ensure wetting a larger area under the tree to compensate the increased root growth. This facilitates more efficient uptake of water and nutrients.

Fertilizer Guidelines in Non-Irrigated Production Conditions

Brazil is the leading producer of oranges in the world with 17.2 million tonnes in 2003, which accounts for 27.7% of total world citrus production (FAO, 2004). The production of mandarins, lime and lemons

TABLE 7. Recommended K rates and minimum number of applications for bearing citrus trees (4 years and older).

Oranges	Grapefruit	Other Varieties	Lower Limit of Application Frequency	
-----K, kg ha ⁻¹ yr ⁻¹ (range)-----			Dry	Fertigation
112-186	112-150	112-186	3	10

Source: Adapted from Tucker et al. (1995)

has increased during the last decade and has made a significant contribution to the local economy with a production of 1 million tonne per year (FAO, 2004). The great majority of the Brazilian citrus-growing area is in São Paulo, where citrus is grown in non-irrigated areas, on soils that are inherently low in fertility, acidic, deep, and well drained.

Guidelines for N, P, and K fertilization of citrus trees in Brazil are developed based on soil and leaf analysis and tree age for non-bearing and young bearing (< 5-year-old) trees or target fruit yield for bearing trees (Grupo Paulista, 1994; Quaggio et al., 1998). Current K recommendations for non-bearing and young bearing trees (< 5-year-old) of all citrus varieties range from 0-20 g tree for 1-year-old tree to 280-370 g tree for 5-year-old trees, where soil exchangeable K is low to medium. For bearing trees, K recommendations differ for oranges grown for frozen concentrated juice versus fresh fruit market, mandarins, limes and lemons (Table 8). Potassium recommendations for each of the above subclasses are further based on the fruit yield goals, as well as soil exchangeable K status. Quaggio et al. (2000) demonstrated the differential response of orange varieties to K fertilization. Optimum fruit size and juice soluble solids content are inversely related to N and K rates. These data have supported recommendation of greater N rates and lower K rates for optimizing fruit yield of oranges grown for juice. In contrast, for oranges grown for the fresh market, the primary interest is on fruit appearance and quality rather than maximum production. Thus, the nutritional management recommendations differ for these trees.

Foliar Fertilization in Calcareous Soils

Soil application of K to calcareous soils may be less effective to ensure adequate K availability to maintain the leaf K concentrations in the desirable range (Hunziker, 1960; Reitz and Koo, 1959, 1960). Foliar application provides a convenient and effective technique to overcome the above problem (Calvert and Smith, 1972; Embleton et al., 1969). Calvert (1969) conducted four experiments using 'Valencia', 'Hamlin', 'Temple', and 'Murcott' citrus trees of different ages grown in calcareous soils (with pH range of 7.2-8.0). Potassium nitrate (KNO_3) was used as the source of K for foliar application at zero (water spray-control), 9.07 or 18.14 kg KNO_3 in 380 L of water. In the case of 'Valencia' orange trees, an additional rate of 27.21 kg per 380 L was also included. The 'Valencia' experiment included 1, 2, and 4 sprays at weekly intervals. Figure 11 shows the leaf K concentration two weeks after the spray. Leaf K concentrations increased with increasing number of

TABLE 8. Potassium recommendations for citrus in Brazil based on expected yield, soil analysis, and fruit quality.

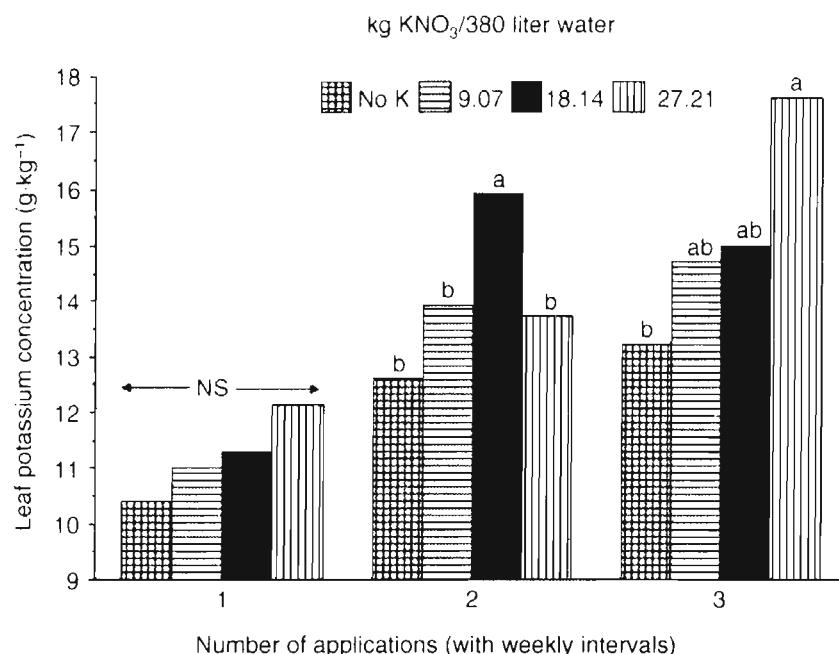
Citrus Variety	Yield Goal Mg·ha ⁻¹	Soil exchangeable K, mmol _C dm ⁻³			
		< 0.7	0.8-1.5	1.6-3.0	> 3.0
Oranges ¹ (FCOJ production)	< 15	55	40	30	0
	16-20	65	45	35	0
	21-30	85	65	45	0
	31-40	110	90	65	0
	41-50	150	110	85	0
	> 50	170	130	90	0
Oranges ¹ (fresh fruit)	< 15	95	75	55	0
	16-20	130	110	85	55
	21-30	150	130	110	75
	31-40	185	165	150	90
	< 40	200	190	170	110
	> 50	200	140	110	40
Mandarins ²	> 15	65	45	20	0
	16-20	75	55	40	0
	21-30	100	75	50	10
	31-40	150	100	70	20
	41-50	185	130	90	30
	> 50	200	140	110	40
Lime ³ and lemons	< 15	75	55	35	0
	16-20	110	90	55	40
	21-30	150	110	75	55
	31-40	200	160	130	75
	41-50	260	190	150	95
	> 50	300	220	190	110

¹FCOJ = frozen concentrated orange juice²Includes 'Murcott' tangor³Tahiti lime

Source: Adapted from Quaggio et al. (1998)

sprays, particularly between 1 and 2 spray treatments. Increasing the number of sprays from 2 to 4 resulted in marginal response at all K concentrations in the spray, except at the highest K concentration. In the latter, the leaf K concentration increased from 14 to 18 g kg⁻¹ with an increase in number of sprays from 2 to 4. Increasing the K concentration in the spray solution increased the leaf K concentration both at 1 and 4 spray applications. In the case of 2 spray applications, leaf K concentrations increased with an increase in KNO₃ in the spray solution from 0 to

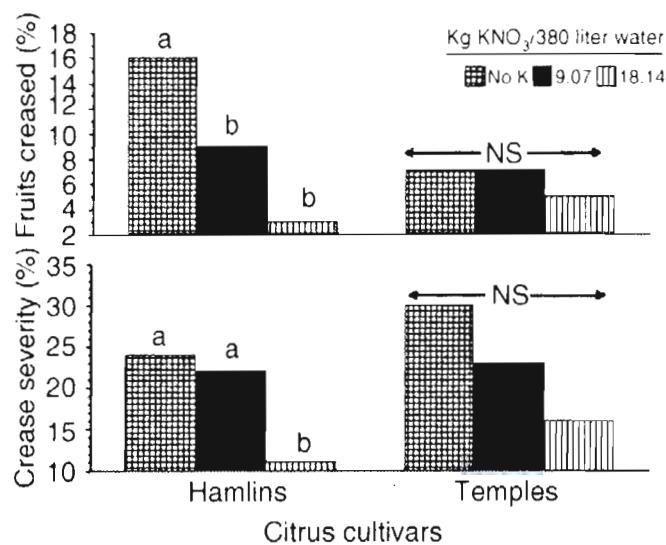
FIGURE 11. The concentration of potassium in the leaves of 'Valencia' orange trees which received 1, 2, or 4 foliar applications of either no K or various rates of KNO_3 (Adapted from Calvert, 1969). Means followed by similar letters, within each spray interval, are not significantly different according to Duncan Multiple Range Test at $P = 0.05$. NS = non-significant.



18.14 kg per 380 L of water. With a further increase in KNO_3 to 27.21 kg, the leaf K concentrations slightly decreased. The fruit yield increased significantly with two sprays per week compared with only one spray per week at both 9.07 and 18.14 kg rates. Fruit yield increased by 70 kg per tree in the trees that received KNO_3 sprays compared with those that were unsprayed. In the 'Hamlin' and 'Temple' experiments, leaf K concentrations increased to 12.3 g kg^{-1} in the trees that were sprayed with KNO_3 (18.14 kg per 380 L water) compared with 9.2 g kg^{-1} in the unsprayed trees. Foliar application of KNO_3 decreased the severity of creasing to 11 and 16% in 'Hamlin' and 'Temple' fruits, respectively, compared with 24-30% severity in the respective cultivars with no foliar K treatment (Figure 12). Foliar application of K increased fruit weight of both varieties.

Boman (1997) reported 3 years of field experiment results on the effects of foliar K spray (fall applications) on mature grapefruit trees in the Indian River production region in Florida. In 1994, 25+ year-old 'Marsh' grapefruit trees on 'Sour Orange' rootstock grown in St Lucie County, FL, were used. The treatments included (1) untreated control;

FIGURE 12. Effects of different rates of foliar K application on percentage of fruits creased and severity of crease in 'Hamlin' and 'Temple' fruits (Adapted from Calvert, 1969). Means followed by the similar letters, within each cultivar and each response parameter, are not significantly different by the Duncan Multiple Range Test ($P = 0.01$). NS = non-significant.



and (2) 3 foliar applications of KNO_3 (13% N, and 38% K) on September 9, October 6 and 27, 1994. In 1995, 30+year-old 'Marsh' grapefruit trees on 'Sour Orange' rootstock, grown in Martin County, FL, were used. The treatments included (1) untreated control; and (2) 2 foliar applications of KNO_3 on September 7 and 28, 1995. This experiment was repeated in 1996 with foliar applications made on October 1 and November 8, 1996. The foliar K application failed to show a significant increase in fruit yield and juice quality. However, the fruit size increased significantly with foliar K applications. For example, in 1994, the increase in fruit diameter during the period from September 10 to November 23 was 11.4% for KNO_3 sprayed versus 8% for control treatment. Boman (1997) also reported that late application of KNO_3 (October–November) were not effective in increasing the fruit size. The magnitude of increase in fruit size, in response to KNO_3 foliar spray, was greater for the smaller fruit compared with that for the larger fruit.

Boman and Hebb (1998) reported the results of studies on effects of post-bloom and summer foliar K sprays on mature grapefruit trees. In 1995, they used 25+year-old 'Marsh' grapefruit trees on 'Sour Orange' rootstock in St Lucie County, FL. The treatments included either untreated control, potassium nitrate spray (KNO_3 , 38% K; at either 11 or 22 kg K ha^{-1} rate), or monopotassium phosphate (MKP, 28.7%; at either 11, 22, or 33 kg K ha^{-1} rates) spray. Foliar sprays were made in

April and May. In 1996, they used 19+ year-old 'Marsh' and 'Star Red' grapefruit trees on 'Swingle citrumelo' rootstock in Indian River County, FL. The treatments included either untreated control, MKP (1, 2, or 3 sprays—April, May, and July) or dipotassium phosphate (DKP, 1, 2, or 3 sprays—April, May, and July). This study also showed that foliar K application increased the fruit diameter compared with that of the fruit in untreated control trees. In most cases, a single application in April was equally effective as that with three applications in April, May, and July.

Boman (2001) conducted further studies on 12+ year-old 'Valencia' orange trees on 'Swingle citrumelo' rootstock grown in Martin County, FL. The treatments included (1) untreated control; (2) monopotassium phosphate (MKP; 8.5 kg Kha^{-1}); (3) potassium nitrate [KNO_3 ; same K rate as in treatment (2)]; (4) calcium nitrate [$\text{Ca}(\text{NO}_3)_2$ with no K]; (5) MKP+ KNO_3 [same K rate as in (2)]; and, (6) calcium nitrate+nutriphite. The foliar sprays were made in February, April, and July-August time period. Boman (2001) concluded that, over the 3-year duration of the trial, KNO_3 or MKP sprayed trees produced 24-29% more fruit per tree compared with that in the untreated trees. This contributed to 28% greater fruit yield and 25% greater solids (per tree basis) for the K sprayed trees compared with those for the untreated trees. The gross return for the K sprayed trees were 24-29% greater than that for the unsprayed trees. In a further study, Boman (2002) confirmed the beneficial effects of KNO_3 spray on increasing the fruit size of 'Sunburst' oranges in Indian River County, FL.

Potassium Source Effects

Response of crops to K sources is based most on the differential supply of Cl^- and SO_4^{2-} in low fertility soils with application of KCl or K_2SO_4 . Deficiency symptoms of sulfur (S) are frequent in crops grown on soils with very low organic matter content and nutrient reserve (Fassbender, 1975). In addition, some researchers have discussed differential anion retention in the soil colloidal complex and consequently nutrient availability to plants (Neptune et al., 1975). Very few studies have evaluated the effects of different sources of K on fruit yield and quality.

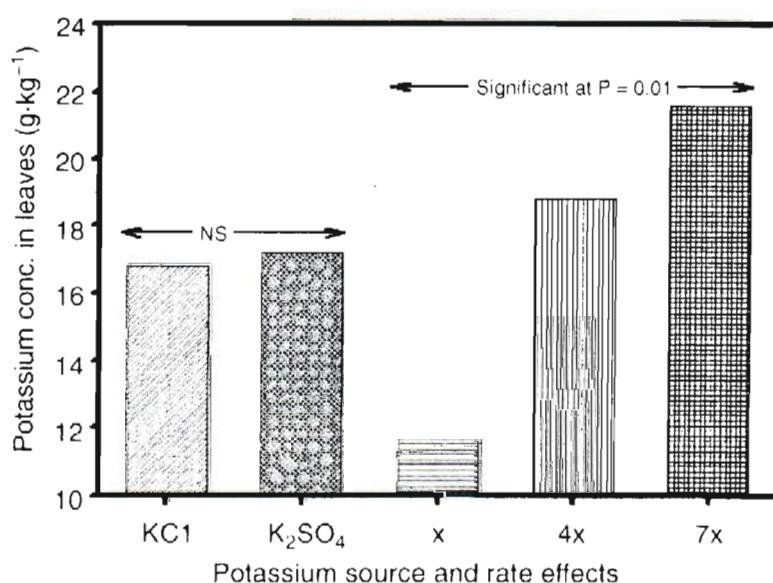
Koo and Reese (1972) conducted three experiments evaluating the effects of K source on young 'Hamlin' orange trees, young bearing 'Marsh' grapefruit trees, and mature 'Valencia' orange trees. The 5-year study on 'Hamlin' orange trees showed generally non-significant effects of K source, applied as either KCl or K_2SO_4 , on trunk diameter or leaf K concentration (Figure 13). Potassium rate, however, had significant

effects on leaf K concentrations in all 5 years of the study. The rate variation for young trees was made possible by changing the K percentage in an 8-2-X (N-P-K) fertilizer blend as 1.7, 6.8, and 12%. The leaf K concentration varied from 12 to 22 g kg⁻¹ with an increase in K concentration in the fertilizer blend.

In a second experiment with 7-year-old 'Marsh' grapefruit trees, 4 year mean fruit yields were 144 and 138 kg per tree for the trees that received K as KCl and K₂SO₄, respectively. The mean fruit yield increased from 124 to 147 kg per tree with an increase in K application from 78 to 156 kg ha⁻¹. Further increase in K rate to 234 kg ha⁻¹ had no significant positive effects on the fruit yield. Fruit weight response was non-significant but the mean fruit weights were 362, 397, and 415 g per fruit for the trees that received K rates of 78, 156, and 234 kg ha⁻¹ yr⁻¹, respectively.

Similar conclusions were also reported in another experiment on the effects of K source on 30-year-old 'Valencia' orange trees. Mean fruit yields across 4 years with 156 kg K ha⁻¹ yr⁻¹ applied as K₂SO₄, KCl, and KNO₃, were 173, 162, and 147 kg per tree per year, respectively. Further increase in K rate to 312 kg ha⁻¹ had no significant effects on fruit yields when using either K₂SO₄ or KCl sources. In the case of

FIGURE 13. Effects of potassium sources and rates on concentration of potassium in the leaves of 'Hamlin' orange trees (Adapted from Koo and Reese, 1972). The effect of K source comparison was non-significant (NS), while the K rate effect was significant at P = 0.01.



KNO_3 , however, the fruit yield increased to 208 kg per tree at 312 kg K ha^{-1} compared with 147 kg per tree at the 156 kg K ha^{-1} rate. This could have been due, in part, to the response to increasing availability of N present in the KNO_3 . The original publication did not indicate if N was supplemented to the low KNO_3 rate treatment to maintain uniform N rates across all KNO_3 rates. The mean fruit yield was 42 kg per tree in the zero K treatment. Leaf K concentrations also showed non-significant effects of K source. Leaf K concentrations during the 5th year of the study varied from 10.1 to 13.1 g kg^{-1} across K sources, and a range of K rates of 156 to $312 \text{ kg ha}^{-1}\text{yr}^{-1}$. The leaf K concentration in the zero K treatment was 4.7 g kg^{-1} .

CONCLUSIONS

In summary, K nutrition plays an important role in fruit production as well as fruit quality. Potassium influences external fruit characteristics including fruit size, weight, green fruit, and peel thickness. These are the attributes which influence the net returns for fruit destined for fresh fruit markets. Likewise, K nutrition also plays a significant role on net returns for fruit destined for juice processing because of K effects of TSS per fruit as well as TSS per unit area of the grove. The K content in the fruit is on par with that of N, that is, $1.2\text{-}1.9 \text{ kg Mg}^{-1}$ of fresh fruit. Thus, the fertilizer blend for citrus is recommended to contain close to 1:1 ratio of N to K. The recommended K rate for optimal production of bearing citrus trees is in the range of $112\text{-}186 \text{ kg ha}^{-1}$ for orange trees, and $112\text{-}150 \text{ kg ha}^{-1}$ for grapefruit trees. Research is lacking to derive definitive conclusions on the potential differences between the dry granular, controlled release, or fertigation methods of delivery of K. Leaf analysis is a good guide for determining the status of K nutrition in citrus trees. Using the K concentration in 4- to 6-month-old non-fruiting terminals of citrus trees, $12\text{-}17 \text{ g kg}^{-1}$ K concentration range is designated as optimal concentration. In some parts of citrus production regions, that is, South Africa and Brazil, the nutritional status of the trees is evaluated by using the leaf analysis sampled from the fruiting terminals. The optimal K status using this method of leaf sampling is $10\text{-}15 \text{ g kg}^{-1}$. In general, different sources of K (i.e., KCl , K_2SO_4 , KNO_3) are equally effective for correction of K deficiencies. The difference among the K sources may be related to anion effects and/or soil properties, for example, saline versus non-saline soils. In calcareous soils, however, foliar K application is more effective compared with soil applications of K.

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