Potassium Requirements for Maximum Yield and Fruit Quality of Processing Tomato

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ABSTRACT. A survey of 140 processing tomato (*Lycopersicon esculentum* Mill.) fields in central California was conducted in 1996–97 to examine the relationship between K nutrition and fruit quality for processing. Quality parameters evaluated were soluble solids (SS), pH, color of a blended juice sample, and the percent of fruit affected by the color disorders yellow shoulder (YS) or internal white tissue (IWT). Juice color and pH were not correlated with soil K availability or plant K status. SS was correlated with both soil exchangeable K and midseason leaf K concentration ($r = 0.25$ and 0.28, $p < 0.01$) but the regression relationships suggested that the impact of soil or plant K status on fruit SS was minor. YS and IWT incidence, which varied among fields from 0% to 68% of fruit affected, was negatively correlated with K status of both soil and plant. Soil exchangeable $K/\sqrt{Mg}$ ratio was the measure of soil K availability most closely correlated with percent total color disorders (YS + IWT, $r = –0.45$, $p < 0.01$). In field trials conducted to document the relationship between soil K availability and the fruit color disorders, soil application of either K or gypsum ($CaSO_4$, to increase $K/\sqrt{Mg}$ ratio) reduced YS and total color disorders. Multiple foliar K applications were effective in reducing fruit color disorders at only one of two sites. In no field trial did K application improve yield, SS, or juice color.

California is a leader in processing tomato production, growing nearly 40% of world supply. Most fruit is processed into concentrated paste, but an increasing percentage of the crop is being used for products using peeled fruit, either whole or diced. Important fruit quality attributes for paste production are soluble solids content (SS) and color of the blended product. Uniformity of color is more important for peeled fruit; even a small area of poorly colored tissue is problematic. Uneven ripening of processing tomatoes is a common problem in California. The typical external symptom is a ring of tissue around the stem scar that upon ripening remains yellow; this symptom, called yellow shoulder (YS), can range in severity from only a few mm wide to discoloration of the top third of the fruit. Internal white tissue (IWT), which can occur throughout the pericarp, is often severe enough to render affected fruit unsuitable for use in peeled, diced products. The occurrence of these disorders has been frequent, but unpredictable.

Potassium nutrition has been linked to tomato quality factors of importance to both paste and peeled product. Increasing nutrient solution K increased lycopene concentration, the predominate carotenoid in mature tomatoes (Trudel and Ozbun, 1971). The incidence of both external and internal blotchy ripening was decreased with increased K supply (Ozbun et al., 1967; Picha and Hall, 1981; Trudel and Ozbun, 1971). Fruit exhibiting blotchy ripening had lower K concentration than normal fruit in both glasshouse (Winsor and Massey, 1958) and field (Picha, 1987) studies. Potassium content of fruit was negatively correlated with fruit pH (Picha, 1987; Winsor and Massey, 1958). Lachover (1972) reported K fertilization increased both fruit yield and SS, even in soil of high K availability.

The relative influence of K nutrition on tomato yield and quality under typical California field conditions is less clear. Soil exchangeable K is high, usually between 0.3 to 0.8 cmol·kg⁻¹. Only

cultivars with a determinate growth habit are used, to allow once-over mechanical harvest. Lingle and Lorenz (1969) reported that although determinate processing cultivars showed leaf symptoms of K deficiency, and had low petiole K concentration, K fertilization did not affect fruit yield, SS or pH. This apparent lack of response to applied K was attributed to the growth characteristics of determinate cultivars, which developed smaller root systems and partitioned a higher percentage of absorbed K into fruit, than semideterminate cultivars (Widders and Lorenz, 1979). Current fertilizer recommendations (Lorenz and Tyler, 1983) suggest that soil exchangeable K >0.2 cmol·kg⁻¹ is sufficient for tomato production. A recent California grower survey found that K application on processing tomato fields averaged only 22 kg·ha⁻¹ (Hartz et al., 1998).

This study was undertaken to reexamine K requirements for optimizing processing tomato yield and quality. This was accomplished by a) a field survey to establish the relationship of soil characteristics to crop K status and fruit quality and b) field trials evaluating various techniques to enhance K supply.

Materials and methods

FRUIT QUALITY SURVEY. In total, 140 processing tomato fields were monitored during 1996 and 1997. Fields were chosen to represent the geographical range of production in central California, a variety of soil types, and harvest dates from early July through late September. To minimize cultivar effects all fields monitored were planted in either 'Halley' or 'Heinz 8892'; these cultivars represented ≈50% of processing tomato production in California in 1997. After crop establishment, a three bed wide × 100-m-long area, of representative vigor, was selected; all sampling was confined to that area to minimize within-field variation in soil characteristics.

Composite soil (top 30 cm) and whole leaf samples (recently expanded leaves, at full bloom growth stage) were collected in each field. Daily max and min air temperatures for each field were also compiled from the nearest computerized weather station of a statewide network. Soil exchangeable K, Ca, and Mg concentrations were measured by atomic emission spectrometry following ammonium acetate extraction (Page, 1982). Plant available soil P was estimated by bicarbonate extraction and measured by spectro-

photometry (Olsen et al., 1954). Soil pH was determined on a saturated paste extract. Leaf N concentration was determined by the combustion method of Sweeney (1989). Leaf K concentration was determined by atomic emission spectrometry following extraction in 2% acetic acid. Leaf P, Ca, and Mg concentrations were determined by inductively coupled plasma atomic emission spectrometry following microwave acid digestion (Sah and Miller, 1992).

Fruit samples were collected 1 to 3 d before commercial mechanical harvest by cutting and shaking 10 to 12 representative plants. A 3-kg subsample of fruit was mechanically juiced and deaerated under a vacuum of 0.09 MPa. SS (°Brix, by refractometer), color (ratio of green (566 nm) to red (650 nm) light reflected from the juice), and pH (1997 samples only) of the juice were measured. Fifty fruit per sample were scored for the number showing YS or IWT. YS was evaluated externally, with fruit showing a contiguous ring of yellow tissue around the stem scar of >2 mm considered affected. IWT was rated internally on fruit cut longitudinally. Fruit were oven-dried, ground and analyzed for K, Ca, and Mg concentration as previously described.

POTASSIUM FERTILIZATION TRIALS. Survey results in 1996 suggested a link between soil cation balance, specifically the relative amounts of soil exchangeable K and Mg, and the incidence of YS and IWT. Field trials were conducted in 1997 to evaluate the effects of soil application of gypsum and K fertilizer on fruit yield and quality. At the University of California, Davis (UCD), five soil treatments were compared to unamended soil: 1 and 2) finely powdered gypsum at 4500 or 9000 kg·ha⁻¹; 3 and 4) K_2SO_4 at 185 or 370 kg·ha⁻¹; and 5) 9000 kg gypsum plus K at 370 kg·ha⁻¹. Gypsum was incorporated in Fall 1996 to dissolve with winter rains, with the Ca displacing some Mg on the soil cation exchange. Potassium was incorporated preplant the following spring. The soil was a Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthent). Four cultivars ('Halley', 'Heinz 8892', 'Ohio 8245', and 'Ohio 8556') were planted and grown using subsurface drip irrigation. A split plot design was used, with soil treatment the main plot, cultivar the split plot. There were four 6 × 15-m replicate plots per soil treatment, arranged in a randomized complete block design.

Soil K application was also evaluated in a field of Heinz 8892 near Clarksburg. The soil was an Omni silty clay (fine, montmorillonitic, calcareous, thermic Fluventic Haplaquoll). Potassium was topdressed after plant emergence in 30-cm-wide bands on either side of the plant row at 0, 185, or 370 kg·ha⁻¹ planted. The field was sprinkler irrigated throughout the season, allowing surface-applied K to move into the root zone. Experimental design was randomized complete block, with four 1.5 × 12-m replicate plots per soil treatment. At both sites soil (top 30 cm) was sampled before soil amendment and analyzed for exchangeable K, Ca, and Mg. Initial soil pH was 7.2 at UCD and 7.4 at Clarksburg. Soil exchangeable K, Ca and Mg levels were 0.83, 9.2, and 12.1, and 0.35, 27.6, and 17.6 cmol·kg⁻¹ at UCD and Clarksburg, respectively. At UCD soil was sampled again when plants reached first bloom stage. Whole leaf samples were collected at full bloom and analyzed for K concentration.

Field trials evaluating the effects of foliar K application on fruit yield and quality were also conducted at UCD and in a field near Collegeville in 1997. At each site plots receiving either three biweekly or six weekly foliar K applications (as K_2SO_4) were compared to unsprayed plots. Applications, which contained K at 11 kg·ha⁻¹ in 280-L·ha⁻¹ spray volume, began just before full bloom. At UCD a split-plot design was used, with number of applications the main plot, cultivar (Halley and Heinz 8892) the split plot. There were four 3 m by 10 m replicate plots per spray treatment arranged in a randomized complete block design. At Collegeville there were four 1.5 × 12-m replicate plots (planted in Heinz 8892) per spray treatment, in a randomized complete block design. Initial soil K, Ca, and Mg levels (top 30 cm) were 0.83, 9.2, and 12.1 and 0.42, 19.7, and 10.6 cmol·kg⁻¹ at UCD and Collegeville, respectively. In all 1997 field trials the following fruit data were collected: total fruit yield, SS and color of a blended juice sample, the percentage of fruit affected by YS or IWT, and the K concentration of dried fruit tissue.

Results

FIELD SURVEY. Soil exchangeable K, and the relative amounts of exchangeable K, Ca, and Mg, were correlated with the tomato

Table 1. Correlation of soil and plant characteristics with tomato quality attributes.

| Characteristic[y] | Soil exchangeable cations[z] | | | K activity ratio[x] | K/√Mg ratio | K/√Ca ratio | K concn (g·kg⁻¹) | | Observed values | |
	K	Ca	Mg				Leaf	Fruit	Min	Max
Leaf K (kg·ha⁻¹)	0.25**	0.01	–0.14	0.29**	0.25**	0.29**	---	0.19*	7	43
Fruit K (kg·ha⁻¹)	0.54**	0.33**	–0.40**	0.55**	0.64**	0.45**	0.19*	---	30	93
SS (°Brix)	0.23**	0.19*	–0.02	0.20*	0.24**	0.14	0.28**	0.09	4.0	7.0
Blended color[w]	0.02	0.15	0.00	–0.02	0.04	–0.05	–0.11	0.09	17	30
Fruit pH	–0.08	–0.17	–0.23	–0.05	–0.03	–0.07	–0.04	–0.07	4.1	4.8
YS (% of fruit)	–0.34**	–0.05	0.36**	–0.38**	–0.41**	–0.32**	–0.22**	–0.35**	0	60
IWT (%)	–0.33**	–0.04	0.30**	–0.36**	–0.38**	–0.32**	–0.17*	–0.32**	0	60
Total color disorders (%)[v]	–0.38**	–0.07	0.35**	–0.42**	–0.45**	–0.32**	–0.19*	–0.38**	0	68
Observed values										
Minimum	0.16	4.9	1.8	0.04	0.06	0.05	7	30		
Maximum	1.67	33.4	19.9	0.27	0.64	0.38	43	93		

[z]cmol·kg⁻¹ basis.
[y]SS = soluble solids, YS = yellow shoulder, IWT = internal white tissue.
[x]K/√Ca+Mg on a soil exchangeable cmol·kg⁻¹ basis.
[w]dimensionless unit, lower value indicates more intense red.
[v]Percent of fruit expressing either YS or IWT.
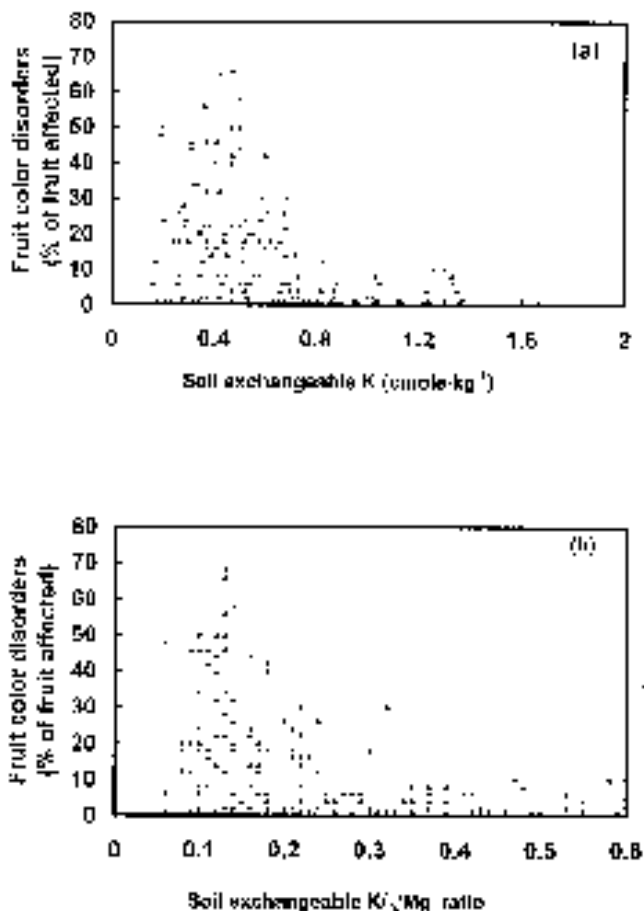[*],[**]Significant at $p < 0.05$ or 0.01, respectively.

Fig. 1. Relationship of tomato color disorders (YS or IWT) to soil exchangeable K√Mg (**a**) or soil K/ ratio (**b**).

color disorders YS and IWT, but had little effect on other fruit quality factors (Table 1). Soil exchangeable K, whether expressed as meq·kg^{-1} or as K activity ratio [K/$\sqrt{Ca + Mg}$, on an exchangeable milliequivalent basis (Brady, 1990)] was negatively correlated with the incidence of YS and IWT. Soil exchangeable Mg was positively correlated with, while exchangeable Ca was unrelated to, the disorders. Soil exchangeable K/$\sqrt{Mg}$ ratio was more closely correlated with the percentage of total color disorders (YS or IWT) than was either soil exchangeable K or K activity ratio. The incidence of YS and IWT were highly correlated ($r = 0.89$, $p < 0.01$).

The practical significance of the relationship of soil cation balance to fruit color disorders was greater than the modest correlations would suggest (Fig. 1). Fields with <0.7 cmol·kg^{-1} soil exchangeable K showed a wide range of color disorder severities, with an average of 20% of fruit affected. Conversely, fields with >0.7 cmol·kg^{-1} exchangeable K averaged only 7% color disorders, with most of the fields in this category showing higher levels of color disorders also having low K/$\sqrt{Mg}$ ratios. Fields with soil K/$\sqrt{Mg}$ > 0.25 averaged only 4% color disorders. Fruit K concentration was more closely correlated with soil exchangeable K/$\sqrt{Mg}$ ratio than with soil exchangeable K alone (Fig. 2). Fruit K varied from 30 to 93 g·kg^{-1} of dry mass, averaging 51 g·kg^{-1}. Fruit Ca and Mg concentration varied widely as well, but averaged only 2 and 3 g·kg^{-1}, respectively. Fruit Ca was negatively correlated with soil Mg/Ca ratio ($r = -0.41$, $p < 0.01$), while fruit Mg was unrelated to that ratio.

Soil exchangeable K was correlated with fruit SS, but the regression relationship (percent SS = 4.9 + 0.46 × cmol·kg^{-1} soil exchangeable K, $r = 0.23$) suggested that the impact of soil K level

on SS was minor. The lack of correlation between the color of blended juice samples and soil cation balance was surprising, given the strong relationship between soil characteristics and fruit color disorders. The relatively small amount of poorly colored tissue typically present in fruit exhibiting YS or IWT apparently had insignificant influence on the color of blended juice.

Midseason leaf K concentration, which averaged only 25 g·kg^{-1}, was more strongly correlated with fruit SS than any measure of soil K, while the reverse was true for YS and IWT. Neither mean daily maximum nor minimum temperature during fruit development (last 6 weeks before harvest) was correlated with any measure of fruit quality (data not presented).

POTASSIUM FERTILIZATION TRIALS. The soil amendment trials confirmed the link between soil cation balance and the occurrence of YS and IWT (Table 2). At UCD, application of gypsum and K fertilization significantly decreased YS and total color defects. The combination of gypsum and K application reduced total color disorders by 54%. Cultivar strongly influenced YS and IWT incidence, with Ohio 8245 and Heinz 8892 showing significantly more color disorders than Halley or Ohio 8856; total color disorders (across soil treatments) averaged 13%, 12%, 5%, and 5%, respectively. There was no significant cultivar x soil treatment interaction. The large difference in susceptibility to YS and IWT between Halley and Heinz 8892 was not seen in the survey, in which these cultivars showed nearly equal percent total color disorders (14% and 15%, respectively).

Soil K application at Clarksburg significantly decreased IWT and total color disorders (Table 2). YS and IWT incidence was higher than at UCD, as the more adverse soil cation balance predicted. The sprinkler irrigation used in this field (necessitated by a slow water infiltration rate that made furrow irrigation
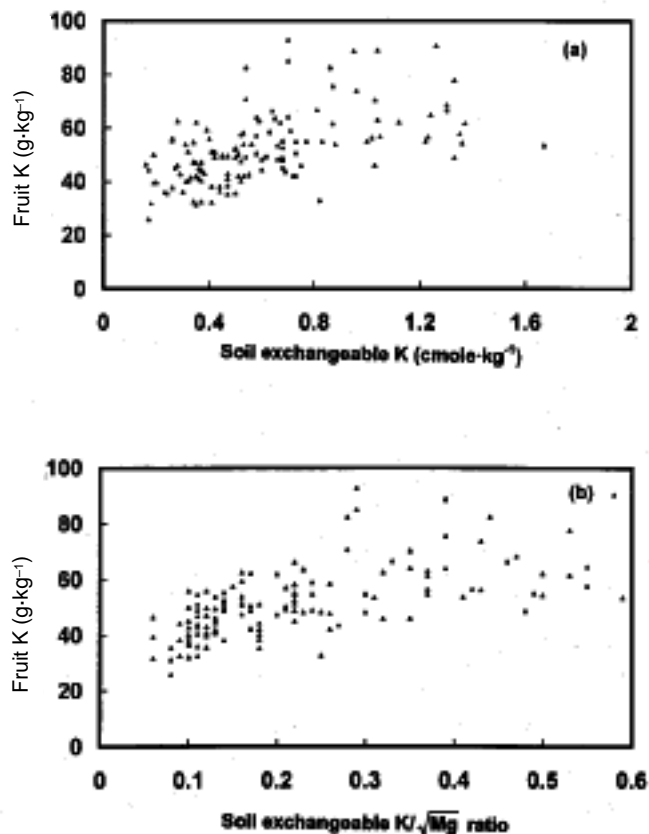

Fig. 2. Relationship of tomato K concentration (dry mass basis) and soil exchangeable K√Mg (**a**) or soil K/ratio (**b**).

Table 2. Effect of soil amendment with gypsum and K on tomato yield and quality.

Soil treatment	Exchangeable K (cmol·kg^{-1})	K/√Mg ratio	Total fruit yield (Mg·ha^{-1})	Soluble solids (°Brix)	Blended color[y]	Color disorder[z] (% of fruit)		
						YS	IWT	total
UCD								
Unamended control	0.83	0.24	106	4.5	22.8	9	8	13
Gypsum, 4500 kg·ha^{-1}	0.90	0.27	105	4.5	23.1	6	6	9
Gypsum, 9000 kg·ha^{-1}	0.86	0.26	102	4.5	22.5	5	5	8
K, 185 kg·ha^{-1}	0.96	0.28	103	4.6	23.0	6	7	9
K, 370 kg·ha^{-1}	1.14	0.33	110	4.5	22.9	7	5	9
Gypsum, 9000 kg·ha^{-1} + K, 370 kg·ha^{-1}	1.16	0.34	106	4.5	22.7	5	4	6
Contrasts								
Gypsum vs. control	NS	NS	NS	NS	NS	**	NS	**
K vs. control	**	**	NS	NS	NS	*	NS	*
Combination treatment vs. control	**	**	NS	NS	NS	*	*	**
Clarksburg								
Unamended control			93	4.3	24.5	14	16	21
K, 185 kg·ha^{-1}			95	4.4	23.3	8	7	11
K, 370 kg·ha^{-1}			94	4.3	24.5	9	8	12
Contrast								
K vs. control			NS	NS	NS	NS	*	*

[z]YS = yellow shoulder, IWT = internal white tissue.
[y]Dimensionless unit, lower value indicates more intense red.
[NS,*,**]Nonsignificant or significant at $p < 0.05$ or 0.01, respectively.

unsuitable) resulted in extensive root development in the surface 10 cm of soil. While banded K application on the soil surface was effective under these conditions, soil incorporation or subsurface banding may have given superior results, and would definitely be preferable under more typical furrow-irrigated fields.

At neither site was fruit yield, SS, or blended color affected by soil treatment. At both sites there was a trend toward increased leaf and fruit K concentration with K fertilization, but treatment differences were not statistically significant.

Foliar K application reduced IWT and total color disorders at UCD (Table 3); the degree of reduction was similar to that seen in the UCD soil amendment trial. Cultivar did not affect color disorder expression, with Halley and Heinz 8892 averaging 7% and 10% total color disorders, respectively; there was no cultivar × treatment interaction. Foliar K had no effect on the incidence of YS or IWT at Collegeville. At neither site did foliar K significantly affect fruit yield, SS, blended color, or fruit K concentration.

Discussion

The field trials showed that only a modest soil exchangeable K level was required for maximum tomato yield, SS, and blended color. The lack of response to applied K in fields with soil exchangeable K as low as 0.35 cmol·kg^{-1} reinforced the results of Hartz et al. (1996) who reported that no more than 0.3 cmol·kg^{-1} soil exchangeable K was required to maximize these parameters. The lack of K treatment effects on fruit SS, and the weak correlation observed between soil K and SS in the survey, suggested that most of the variability of SS observed in commercial fields is due to factors unrelated to K availability, such as irrigation management or fruit yield (Dumas et al., 1994; Panagiotopoulos and Fordham, 1995). The inability to significantly increase either leaf or fruit K by even the large K applications used in the soil amendment trials reinforced the findings of Lingle and Lorenz (1969) and Widders and Lorenz (1979) that the growth character-

Table 3. Effect of foliar K applications on tomato yield and quality.

Location	Applications (no.)	Total fruit yield (Mg·ha^{-1})	Soluble solids (°Brix)	Blended color[y]	Color disorder[z] (% of fruit)		
					YS	IWT	Total
Univ. of Calif., Davis							
	0	95	4.3	22.8	8	8	13
	3	93	4.4	22.7	5	4	7
	6	93	4.4	24.0	4	3	5
Linear trend		NS	NS	NS	NS	*	*
Collegeville							
	0	132	4.7	22.8	32	29	41
	3	125	4.9	22.5	29	22	36
	6	127	4.8	22.0	32	23	40
Linear trend		NS	NS	NS	NS	NS	NS

[z]YS = yellow shoulder, IWT = internal white tissue.
[y]Dimensionless unit, lower value indicates more intense red.
[NS,*]Nonsignificant or significant at $p < 0.05$, respectively.

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istics and rooting pattern of determinate tomato cultivars make it difficult to substantially influence K uptake. In typical California field conditions soil K status is apparently a minor factor in determining fruit yield, SS, or blended color (the primary quality factors for paste processing), justifying the low level of K fertilization currently employed (Hartz et al., 1998).

Maximizing the quality of tomatoes for peeling clearly required greater K supply than that required for maximum fruit yield. The link between K nutrition and the development of YS and IWT has been reported in glasshouse and field production of fresh market tomato (Picha and Hall, 1981; Winsor and Massey, 1958). The modest correlation between soil K and these color disorders in the field survey emphasized that soil extractable K is a useful, but imperfect, indicator of K availability. Alternative soil test methods such as rate of K released into soil solution (Cassman et al., 1990) or cation resin extraction (Skogley et al., 1990) have been reported to be more accurate predictors of crop K uptake. Also, soil physical characteristics (structure, compaction, aeration, etc.) and management practices (most notably irrigation method, timing, and volume) that influence root density and function can affect K phytoavailability, since crop K uptake is a diffusion rate-limited process.

It is widely recognized that crop K uptake is affected by the activity of other soil cations, predominately Ca and Mg. This study found that soil Mg had greater influence on crop K status, and YS and IWT, than did soil Ca. Soil K/$\sqrt{Mg}$ ratio was the variable most closely correlated to fruit K concentration, and the incidence of color disorders. Soil application of gypsum at UCD reduced color disorders, apparently by reducing exchangeable Mg. Soil exchangeable K was virtually unaffected by gypsum application; exchangeable K displaced by applied Ca was replenished by nonexchangeable (fixed) K from soil colloids (Brady, 1990). Calcium application could be counterproductive in soil with limited nonexchangeable K.

The importance of soil Mg to the K status of tomato agreed with the findings of Carlson and Rosen (1983), who reported that, on a survey of prune (*Prunus domestica* L.) orchards in California, soil exchangeable Mg was more closely correlated with leaf K concentration than any measure of soil K. In neither that study nor the present one was the mechanism by which soil Mg influenced crop K status clear. In a subsequent study Rosen and Carlson (1984) found that varying Ca/Mg ratio (and consequently the K/Mg ratio) in solution culture did not affect K uptake of *Prunus* rootstocks. It is possible that soil Mg had an indirect effect on K availability through its influence on soil physical properties. Mg has been shown to have deleterious effects on soil structure, water infiltration rate and hydraulic conductivity (Keren, 1991; Alperovitch et al., 1986; Summer, 1993). Further investigation of the K/Mg interaction is warranted.

Soils can be amended to reduce YS and IWT, the level of K or Ca application required to substantially improve fruit quality dependent on soil characteristics. As demonstrated by the UCD and Clarksburg trials, high levels of amendment may be required to substantially reduce color disorder incidence. This would particularly be true of soils with high K fixation capacity. Cassman et al. (1989) reported that 86% of K at 1440 kg·ha^{-1} applied over a 3-year period was fixed in one central California soil. Since no yield advantage would be expected if a soil had >0.3 cmol·kg^{-1} exchangeable K, it would be cost prohibitive to amend problem soils with either K fertilizer or gypsum unless a significant premium was paid for improved fruit quality for peeling.

Multiple foliar K application was effective in reducing fruit color disorders at UCD, but was ineffective at Collegeville, where soil cation balance was highly unfavorable. A major limitation of foliar application is the amount of K that can be applied. Currently few California processing tomato growers apply foliar K, and those who do seldom make more than two applications. The effect of that practice on YS and IWT incidence in fields with severe K/Mg imbalance is questionable.

The fact that numerous fields in the survey had little or no YS or IWT despite low soil K, and low fruit K concentration, suggested that factors other than K nutrition influenced development of color disorders. Environmental influences such as season of the year (Picha and Hall, 1981), fruit temperature (Ventner, 1965), and relative humidity (Lipton, 1970) have been reported to affect YS severity. In the survey no correlation was observed between air temperature and the color disorders. It was observed that fruit directly exposed to the sun had higher incidence of YS, and more severe symptoms on affected fruit. No correlation was observed between either leaf N or P level and the color disorders. It was surprising that fruit K content was not correlated with plant N status. Numerous studies have reported a link between N availability and total cation uptake (Hansen, 1972; Cunningham, 1964; Nielsen and Hansen, 1984), yet in survey fields K concentration, the predominate cation in fruit, varied from 30 to 93 g·kg^{-1}, and was unrelated to leaf N level.

Despite the uncertainty regarding factors other than K that contribute to YS and IWT development, it is clear that K plays a dominant role. Only 5 of 45 fields with soil extractable K ≥0.7 cmol·kg^{-1}, and 2 of the 45 fields with soil K/$\sqrt{Mg}$ >0.25, had significant levels of color disorders. These relationships will allow the processing tomato industry to use routine soil testing to rank fields for the relative danger of encountering severe YS and IWT expression.

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