4. The role of potassium and chloride in crop nutrition and production

4.1. Field crops

4.1.1. Wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.)

Small grain crops with relatively short growing periods need a high level of K supply early in the season (Forster, 1982). In terms of kg ha^{-1} wheat and other cereal crops require about the same amount of K as N and in some instances the need for K may exceed that of N (Kemmler, 1983). The total consumption of K from soil by wheat yielding > 10 t ha^{-1} varies from 160 to 242 kg K ha^{-1} (Kemmler, 1983). Soil available K level, amount of applied K fertilizer, soil fertility level and crop varieties influence total K uptake. Generally the final quantity of K in cereals is 5 kg t^{-1} grain and 10 to 20 kg t^{-1} straw for a wide range of conditions in the absence of deficiencies or excesses (Mengel, 1982).

Potassium accumulation in aerial parts reaches its peak before the grain filling both in wheat (Kafkafi *et al.*, 1978; Kemmler, 1983) and in barley (Bao and Xu, 1993). Wheat growing under optimum conditions will take up as much as 2 kg K ha^{-1} per day during periods of peak demand at midseason (Beaton and Sekhon, 1985). Wheat can contain as much as 500 kg K ha^{-1} at ear emergence, but about 60% of it returns to the soil at harvest time (Kafkafi *et al.*, 1978) via elution from aging leaves, leaf fall, and perhaps also by outward movement from mature roots after full heading (Beaton and Sekhon, 1985) and from the standing straw due to rainfall before harvest. Therefore, leaf analysis results from sampling of a mature cereal crop cannot represent maximum K demand and maximum K uptake rate.

Large increases in the yield of wheat and barley were recorded from KCl application in the Great Plains of USA. Because the concentration of soil available K were quite large, it was suggested that the response was due to Cl rather than to K (Fixen, 1993). Comparing two ammonium fertilizers with the same amount of N, yield increase ranged from 470 to 2150 kg ha^{-1}, with an average of 1076 kg ha^{-1} due to NH_4Cl as compared to $(NH_4)_2SO_4$. Fixen *et al*. (1986a, b), Gaspar *et al*. (1994) and Engel *et al*. (1994) described the responses of wheat and barley to Cl in some detail.

Some of the above responses to Cl were attributed to either suppression of root or foliar diseases or to enhancement of host tolerance to the disease (Fixen, 1993). Leaf spots and tissue necrosis are caused by inadequate Cl nutrition rather than pathogen infection (Engel *et al*., 1997). The so-called 'Cl-deficient leaf spot syndrome' of wheat varies with cultivar and disappears with application of Cl-containing fertilizers (Mortvedt *et al*., 1999). The symptoms increased exponentially as the content of Cl in the whole plant at head emergence dropped below 1 g kg^{-1} DM.

4.1.2. Rice (*Oryza sativa* L.)

Soil flooding alters the chemistry and availability of soil K. Under reducing conditions, Fe^{2+}, Mn^{2+} and NH_4^+ are released in the soil by various processes and displace K from the exchange sites, increasing its concentration in the soil solution and its availability to rice (Patrick and Mikkelsen, 1971). As a result, K losses by leaching in rice fields could be substantial (De Datta and Mikkelsen, 1985).

The pattern of K uptake follows most closely that of vegetative growth. Even before the booting stage, 75% of the maximum K content has been taken up, and most of the remaining uptake is completed before grain formation begins, very similar with the pattern of K uptake in wheat. About 20% of the K taken up before full heading is translocated to the panicles and the rest remains in the vegetative parts at maturity (De Datta and Mikkelsen, 1985).

Interestingly, the F_1 hybrid rice cultivars take up more K due to a well-developed root system and vigorous growth than do the ordinary rice varieties (Xu and Bao, 1995). For example, at the same yield of 7.5 t ha^{-1} of rice grains, the K uptake by hybrid rice was 218 kg ha^{-1} compared to only 156 to 187 kg ha^{-1} by other ordinary rice cultivars. The yield potential of hybrid rice is greater than that of ordinary varieties, when soil fertility is high or large amounts of fertilizers are used (Table 4.1), but hybrid varieties often yield less than some ordinary varieties when grown on K deficient soils (Bao, 1989). The beneficial effect of K is more likely with hybrid rice than with ordinary varieties (Fan and Tao, 1981).

Table 4.1. Response of hybrid and ordinary short-culm rice to K fertilization in Jiangxi Province, China.

Variety	No. of experiments	Mean K application (kg K_2O/ha)	Yield (kg ha^{-1})		Yield increase (kg grain kg^{-1} K)
			-K	+K	
Hybrid rice	28	62.3	5456	6579	18.0
Short-culm rice	36	37.4	4836	5261	11.4

Source: Fan and Tao (1981).

Rice is relatively tolerant of Cl. When rice shoots had less than 3 g Cl kg^{-1} DM, irrigation with water containing 50-150 g Cl m^{-3} increased rice yield (Fig. 4.1). There were no negative effects of Cl on the yield or quality of rice grains when the mature straw contained about 12-13 g Cl kg^{-1} (Zhu and Yu, 1991; Huang *et al.*, 1995). Rice could tolerate soil Cl levels as high as 0.4-0.8 g kg^{-1} (Zhu and Yu, 1991) or 0.3-0.5 kg m^{-3} in the irrigation water (Yin *et al.*, 1989).

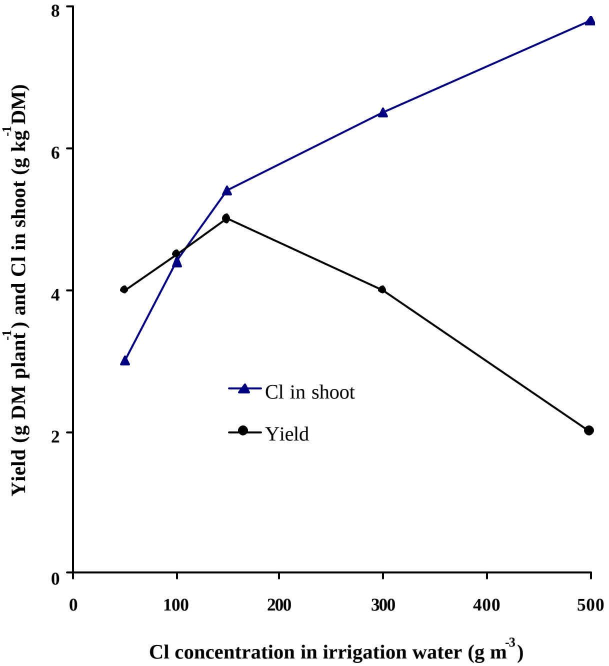

Fig. 4.1. Effect of chloride concentration in the irrigation water on yield and on chloride concentration in the shoot of rice (Based on Yin *et al.*, 1989).

4.1.3. Corn (*Zea mays* L.)

Potassium accumulation during the early growth stages of corn is faster than that of dry matter (Welch and Flannery, 1985). The dilution effects and translocation of K from leaves and stalks to the cob and grains cause a rapid decline in K in the vegetative shoot. Peak demand for K is in the short pretasseling stage (14-21 days) when about 38% to 59% of total K uptake occurs (Hanway, 1962). In this short period, average daily uptake of K ranges from 2.31 to 10.74 kg ha^{-1} leading to 87 to 396 kg ha^{-1} of total K in the plant at grain harvest (Welch and Flannery, 1985). To meet such a large demand K must be applied as a base fertilizer or during the very early growth stages to ensure an adequate K supply.

Adding K to deficient soils increases water transpiration loss from corn leaves due to the larger plant mass (Peaslee and Moss, 1966), but the relative increase in transpiration is less than the increase in dry matter and the decrease of evaporation (Welch and Flannery, 1985), so the net effect is that K increases plant water use efficiency.

Reduced photosynthesis in K deficient leaves was ascribed to reduced stomatal apertures and could be reversed by supplying K (Peaslee and Moss, 1966). The critical concentration for photosynthesis is 2 g K kg^{-1} (on fresh weight basis). Therefore, this concentration must be exceeded, particularly in the upper leaves that receive relative sufficient light and have the greatest potential for photosynthesis for successful corn production.

Corn benefits less than other cereal crops from applying Cl (Fixen, 1993). Three N sources (ammonium chloride, ammonium sulphate and ammonium nitrate) produced almost identical yields of corn grown on a silt loam soil (pH 6.7) as long as the Cl content was below 600 kg ha^{-1} (Meelu *et al.*, 1990). Applications of Cl had no deleterious effects on the growth or yield of corn, even at rates of 728 kg Cl ha^{-1} (Parker *et al.*, 1985).

Chloride supply may become limiting for the significantly larger yields that can be achieved under more intensive production practices. Heckman (1995) found positive responses to Cl application up to 400 kg Cl ha^{-1} in maximum yield experiments. Grain yields were positively correlated with increases in ear leaf Cl concentration. He concluded that enhanced levels of Cl nutrition may favorably influence corn production as a result of: (i) retention of water in plant tissues and extending the period of grain fill, (ii) partitioning more photosynthate into grain, and (iii) suppression of stalk rot disease.

Potassium plays a vital role in reducing stalk lodging in corn. High yield corn hybrids are more effective in translocating photosynthates from leaves and stalks to grain but have more mechanical stress on the stalk due to the greater weight of ears and lower concentrations of soluble solids in the stalks (Campbell, 1964). Hence, maintaining a sufficient supply of K to prevent lodging needs more attention in hybrid corn varieties. Heckman (1995) obtained a linear decrease in lodging with increasing rates of Cl application.

The incidence of stalk rot in corn decreased with increasing rates of KCl, whereas K_2SO_4 or KH_2PO_4 had little or no effect (Younts and Musgrave, 1958; Heckman, 1995).

4.1.4. Cotton (*Gossypium hirsutum*)

Potassium deserves special attention in cotton production because of its high uptake rate, and less efficient K uptake mechanism compared to many other crops, especially when planted on sandy soils of inherently low available K (Kerby and Adams, 1985). Both formation in rapid-maturing, short-season cultivars puts a strong demand on the internal plant K, because the concentration in the boll exceeds 25 g K kg^{-1} on a dry weight basis (Qing, 1988; Bao, 1989). This K is required mostly by the bur itself and is not translocated to the seeds or to the fibers (Rosolem and Mikkelsen, 1991).

Cotton yield suffers more often from inadequate K fertilization than soybean, corn, vetch and wheat crops (Cope, 1981). The common recognized visual symptom of K deficiency is *cotton rust*, yellowish white mottling of the leaf that begins on older leaves (Kerby and Adams, 1985). The visual deficiency symptoms of modern, more heavily fruiting, cultivars, however, occurs first in the upper canopy and progresses from the younger to the older leaves (Bednarz and Oosterhuis, 1996). A disorder called *premature senescence* (young leaves turn red during boll filling and shed) is associated with low levels of K in the leaves and a big boll load (Wright, 1999).

There are many surveys on the minimum soil available K for achieving maximum yield. Critical values in the USA are about 2.3-2.6 mmol kg^{-1} of NH_4OAc-extracted exchangeable K on sand-loam soil and 3.0-3.2 mmol kg^{-1} on clay-silt soils (Kerby and Adams, 1985). This is also consistent with the suggested critical K value of 2.6-2.9 mmol kg^{-1} (100-113 mg kg^{-1}) for soils in China (Bao, 1989).

Cotton petioles are more sensitive to changes in available soil K levels than other organs (Bao, 1989; Oosterhuis and Bednarz, 1997) (Fig. 4.2; Qing, 1988). Thus petiole analysis is used to assess K status. The K concentration in the leaf and petiole decreases with plant age. As an indeterminate-type plant, cotton changes its growth pattern with climate. The minimum K concentration in older petioles associated with maximum yield varies greatly from 26.2 to 53.0 g kg^{-1}, between locations and years (Kerby and Adams, 1985). Oosterhuis and Bednarz (1997) found that decrease in leaf physiological processes and plant growth did not occur until the petiole K concentration fell below 8.8 g kg^{-1} on a dry weight basis.

According to Pettigrew (1999), a deficiency in K altered the leaf carbohydrate and water status of cotton plants by increasing the glucose and fructose concentrations and by elevating the leaf turgor. The elevated carbohydrate concentrations remaining in the leaves reduced the amount of photosynthate availabe for reproductive sinks, and thereby decreased lint yield and fiber quality.

The total K uptake of cotton varies according to soil K supply. Maximum yield was observed when 0.10 to 0.13 kg K was taken up for each kg of lint produced (Kerby and Adams, 1985). A continuous adequate supply of K is needed throughout the entire period growth and development. However, the time of maximum uptake is during the early blooming stage. About one third of the total K is taken up during a 12 day period (72-84 days after emergence) from squaring to early blooming stage (Halevy, 1976). Over 80% of the total Cl in cotton is found in the leaves and stems, and only a small part in the roots and seeds (see Fig. 3.21).

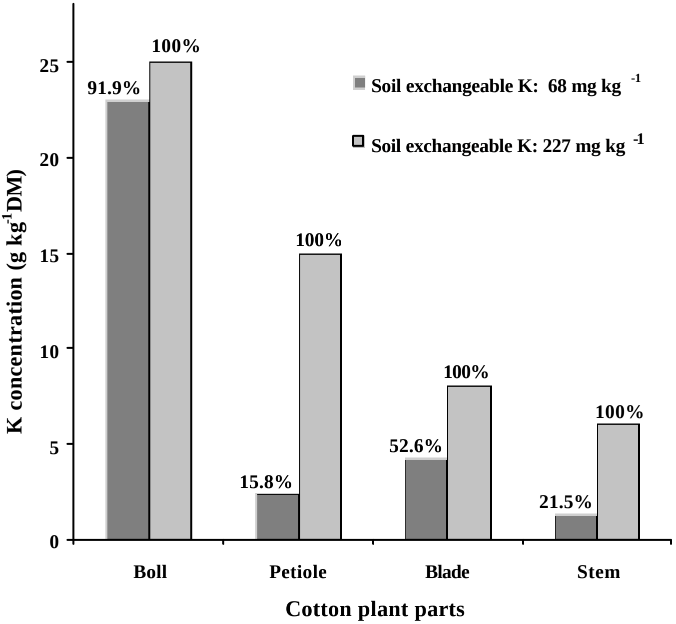

Fig. 4.2. Potassium concentration in different organs of cotton grown on soils at two levels of exchangeable K, 227 and 68 mg kg^{-1}, respectively (Source: Qing, 1988).

The cotton seedling is very sensitive to Cl above 100-200 mg kg^{-1} (Tan and Shen, 1993). So, fertilizers like NH_4Cl and KCl are not recommended for placement in the seed-row. However, after the seedling stage, cotton can tolerate high salt levels in the soil. No changes in cotton yield or quality were observed when Cl concentrations were below 1600 mg kg^{-1} soil (Table 4.2).

Table 4.2. Effects of chloride on the yield and quality of cotton.

Fertilizer Cl (mg Cl kg^{-1} soil)	Seed emergence (%)	Fiber yield (g pot^{-1})	Biological yield (g pot^{-1})	Fiber length (mm)
0	100	6.12	77.6	28.7
100	97	5.93	78.5	28.5
200	100	5.97	76.4	29.1
400	87	5.91	82.9	29.0
800	60	8.01	90.7	29.8
1600	3	7.27	70.9	28.0
3200	0	3.14	63.4	28.0

Source: Tan and Chen (1993).

4.1.5. Groundnut (*Arachis hypogaea* L.)

Groundnut pod yield responded to K when available soil K was extremely low, but there was an adequate supply of Ca to bring about good filling of the fruit (Brady and Colwell, 1945). They showed that K affects yield through its influence on plant size rather than on kernel development. The K, Mg, or Ca supply status did not affect the kernel % of oil in the large and medium size kernels. The minimum sufficiency levels for maximum yield were 10 g K kg^{-1} leaf and 20 mg K kg^{-1} soil for Mehlich 1 extraction (Walker *et al.*, 1989). The plant contained the largest amount of K at the pod ripening stage before it decreased by 26% at harvest time (Halevy and Hartzook, 1988). The total uptake of K of a high yielding cultivar reached 244 kg ha^{-1}, but only 16% was in the pods (Halevy and Hartzook, 1988).

The vegetative growth of groundnut is reasonably tolerant to Cl salinity, but the pod yield is severely reduced when irrigated with water with an EC of 4.5 dS m^{-1} (Silberbush and Lips, 1988). These authors found that under field conditions the sensitivity of the groundnut plant to salt is mainly the result of damage to the gynophore when it touches the upper soil layer. However, application of Cl stimulated growth and increased seed yield when the total Cl concentration in the soil was below 137 mg kg^{-1}, but higher soil Cl levels in the range of 400-600 mg kg^{-1} reduced almost every physiological index (Wang *et al*., 1989).

4.1.6. Soybean (*Glycine max* L. Merr.)

The amount of K accumulated in soybean plants varies with its availability in the soil, but the seasonal patterns of K accumulation and distribution among plant parts are similar at all soil K availability levels (Hanway and Johnson, 1985). The total amount of K taken up by the plants ranged between 63 and 129 kg ha^{-1} at low and high soil K levels, respectively. With high K fertility leaf % K of soybean at the beginning of seed development and in the mature seeds, varied from 12 to 16 g kg^{-1} and 15 to 18 g kg^{-1}, respectively, but did not vary appreciably among different cultivars from 18 genetic lines (Hanway *et al*., 1984; Loberg *et al*., 1984).

Soybean takes up and accumulates K throughout the entire growing season, therefore any deficiency during the growing season will reduce final yield. During the seed filling period, although the rate of K uptake decreases rapidly, there is a risk that K in the vegetative plant parts will be retranslocated to the developing seeds. Thus, K uptake from the soil must continue to avoid serious premature depletion of K in the leaves (Coale and Grove, 1991). The symptoms of late-season K deficiency in soybean (marginal leaf browning in the upper leaves of the plant) should not be confused with Cl toxicity which has very similar symptom (Snyder and Ashlock, 1996).

In field experiments, seed yields and Cl levels in leaves of five soybean cultivars were not affected by K application rates, but the yields decreased with increasing leaf Cl levels (Snyder *et al*., 1993). Soybean leaf scorch is always associated with excessive amounts of Cl in the leaves (Parker *et al*., 1986). Incipient leaf damage was seen at Cl level of 186 mg kg^{-1} soil and plant death occurred at 370 mg kg^{-1}. The average Cl level in the leaves of susceptible cultivars was 16.7 g kg^{-1}, i.e., 18 times greater than the 0.9 g kg^{-1} found in the leaves of tolerant cultivars (Snyder *et al*., 1993).

In grafted soybean cultivars grown in a saline solution of 49.3 mM Cl, the onset, severity and visual symptoms of foliar injury were controlled by the genotype of the rootstock and were correlated with leaf Cl concentration (Grattan and Mass, 1985). All four genotypes, when grafted on rootstocks that translocated Cl to the shoots, were sensitive to Cl. The scions therefore do not appear to restrict translocation of Cl from the roots to the leaves (Grattan and Mass, 1985).

Soybean tissue water content was much less influenced by KCl fertilization, but its influence differed between soybean cultivars. Crops grown on salt affected soils often show symptoms of toxicity. Chloride toxicity from KCl application was reported for soybean grown on Atlantic Coastal Plain soils (Parker *et al*., 1983).

4.1.7. Potato (*Solanum tuberosum* L.)

Potatoes demand a high level of nutrients in soil, particularly K, due to their relatively poorly developed root system (Perrenoud, 1983). Potatoes are regarded as an indicator crop for soil K availability (Ulrich and Ohki, 1966) because K uptake and total tuber yield are closely related to the supply of available K from soil and fertilizer. For example, the cultivar *Russet Burbank* yielded 54 and 95 t tubers ha^{-1}, containing 20.6 to 25.8 g K kg^{-1} DW and with a total K in the tubers ranging from 230 to 445 kg ha^{-1} (Roberts and McDole, 1985).

It is difficult to set universal critical ranges for soil K, because of variable growing conditions, climate, the large number of available cultivars, and great differences in tuber yield in publication data. Surveying results from the former Soviet Union (Beljaev, 1979, cited by Perrenoud, 1983), the USA (Roberts and McDole, 1985) and England (Birch *et al*., 1967) showed that for high yielding potatoes the exchangeable K in the range 100-200 mg kg^{-1} could be regarded as deficient. Recommended rates of K fertilization ranged from 150 to 300 kg ha^{-1} where potatoes are grown on K deficient soils, depending on the yield potential of the area (Roberts and Mc Dole, 1985).

Relative to K_2SO_4, KCl significantly delayed potato tuber development in a pot experiment, as a result of lower osmotic potentials, higher water contents and greater shoot growth in the KCl-treated plants (Beringer *et al*., 1990).

Table 4.3. Effects of K and its source on potato yield, grade (size), hollow heart (HH) and brown center (BC).

K application		K		Yield		In 20 largest tubers	
May 18	July 7	Source	Total	>170 g $tuber^{-1}$	<113 g $tuber^{-1}$	HH	HH + BC
(kg K ha^{-1})				(t ha^{-1})		(%)	
0	0	None	45.2	14.8	10.6	15.0	20.0
93	0	KCl	49.8	22.5	10.6	1.2	6.2
93	0	K_2SO_4	52.4	18.3	10.6	5.0	10.0
279	0	KCl	62.3	29.9	10.9	2.5	6.2
279	0	K_2SO_4	57.3	21.7	13.3	2.5	12.5
93	372	KCl	63.3	30.9	9.9	0.0	10.0
LSD 0.05			6.2	5.6	5.4	5.3	8.1

All treatments with constant N, P and S were banded at planting.
Source: Jackson and Mc Bride (1986).

The decline in starch accumulation at K concentrations greater than 20-25 g kg^{-1} DM in tubers (Marschner and Krauss, 1980) could be explained in terms of an osmotic optimum for starch synthesis (Wright and Oparka, 1990). The favorable effect on tuber starch content with K_2SO_4 as compared to KCl has been attributed to a higher translocation of assimilates into the tubers with K_2SO_4 (Haeder, 1976).

The application of KCl as compared to K_2SO_4 increased both individual tuber weight (by over 170 g $tuber^{-1}$) and the grade percent, and reduced the percentage of hollow hearts and brown centers (Table 4.3). The larger concentrations of Cl and total cation content in the tubers reduced tuber susceptibility to heat and moisture stress. Westermann *et al.* (1994) suggested that N or K fertilizers can be applied to potatoes according to soil test values and crop requirements, without considering the K fertilizer source.

4.1.8. Sugarbeet (*Beta vulgaris* L.)

Potassium is the cation that is taken up in the largest amount by sugar beet. Each ton of fresh harvested roots removes 1.3-2.8 kg of K. Depending on yield, the total K removed varies between 39 and 176 kg ha^{-1} (Moraghan, 1985). The most conspicuous field-observed feature of K deficiency is the appearance of variable amounts of brownish, dead tissue on the older blades of well-developed plants. The first definitive sign of K deficiency in the field is the development of a marginal, interveinal chlorosis toward the distal end of the older leaf blades (Moraghan, 1985).

The K requirement of sugarbeet in the field at certain levels of K deficiency can be nearly replaced by Na (Draycott and Bugg, 1982). Both K and Na are usually required on soils with little available K. When application of K fertilizer results in no or little increase in root yield, changes in K and Na in both root and leaf tissues are relative small (Draycott *et al.*, 1970). Because of the negative interaction between Na and K in sugar beet nutrition and a possible separate nutritional role for Na, diagnosis of K deficiency is difficult.

Sugar beet requires large amounts of Cl. A Cl concentration of 0.18-0.29 g kg^{-1} DM in the petioles was found to be indicative of extreme Cl deficiency for beets. The critical Cl concentration was about 1.4 g kg^{-1} DM in the leaves and 5.7 g kg^{-1} DM in the petiole; an adequate concentration in the petioles was 7.1 g kg^{-1} DM (Ulrich and Ohki, 1956). The Cl content of sugar beet tops at harvest varied from 28 to 148 kg ha^{-1} depending on the soil Cl level (Moraghan, 1987). Chloride applications of up to 1600 mg kg^{-1} produced positive effects on sugar beet, and in clay soils applications as high as 3200 mg kg^{-1} were tolerated before any yield reduction was observed (Jing *et al.*, 1992).

4.2. Vegetables

4.2.1. Tomato (*Lycopersicon esculentum* Mill.)

Potassium concentration in tomato leaves varies between 31-61 g K kg^{-1} leaf dry matter, and in fruits within 42-52 g K kg^{-1} fruit dry matter, according to the rate of K fertilization (Borkowski and Szwonek, 1978). In hydroponics experiments, visual symptoms of K deficiency appeared only on adult leaves where the K deficiency threshold value was 12 g K kg^{-1} leaf dry matter (Pujos and Morard, 1997). Wilcox (1964) reported an increase in the K content of tomato juice from 29 to 47 g kg^{-1} after applying 500 kg K ha^{-1}. Tomato fruit yield and leaf tissue % K increased linearly with increasing rates of applied K, independently of the K source (KCl, K_2SO_4, and KNO_3) (Locascio *et al.*, 1997). A suggested critical K concentration in young tomatoes is 23 g kg^{-1} DM (Renner *et al.*, 1995).

The transition to more intensive production systems for tomatoes to increase yield has required more K. In Florida, 4.25 kg K t^{-1} tomatoes has been used as a normal K consumption index (Geraldson, 1985). Using this index, yields of 350 t fruit ha^{-1} obtained in hydroponic systems (Kougart, 1982) would require about 1500 kg ha^{-1} of K.

A survey of 140 processing tomato fields (Hartz *et al.*, 1999) showed that the incidence of fruit color disorders yellow shoulder (YS) or internal white tissue (IWT) in processing tomatoes was negatively correlated with the K status of both soil and plant. Soil application of K reduced YS and total color disorders. Soluble solids (SS) was also correlated with both soil exchangeable K and midseason leaf % K (Hartz *et al.*, 1999). Potassium application increased the red color of tomatoes (Trudel and Ozbun, 1971) as well as the citric acid, malic acid and total soluble solids in the fruit (Usherwood, 1985).

The response of tomato to salinity has been studied intensively (Albu Yaron *et al.*, 1993; Satti *et al.*, 1994; 1995; Satti and Al-Yahyai, 1995; Pasternak and De Malach, 1995). Tomatoes are especially sensitive to salinity at the young seedling stage (Satti *et al.*, 1994; 1995). Chloride salts reduced plant dry weight, increased defoliation and accumulation of Cl in the leaves, and caused a sharp reduction in photosynthesis, leaf water potential and stomatal conductance (Pasternak and De Malach, 1995). In contrast, these parameters were not affected by leaf Na concentrations of up to 478 mM in the tissue water. Different tomato cultivars responded differently to the saline treatments. Salinity had no significant effect on the number of fruits or on the fruit set of tomato (Satti *et al.*, 1995). Tomato growth was not affected as long as the Cl concentration in the plant tissue was less than about 30 g kg^{-1} DM (Kafkafi *et al.*, 1982).

Chloride can improve fruit quality by reducing the water content of the fruit and thereby increasing the content of dry matter and of aromatic and other components that contribute to taste and appearance (Pasternak and De Malach, 1994). Chloride salinity during the cell enlargement stage reduced cell volume growth by lowering the amount of water transported to the fruit (Ho *et al*., 1987). High dry matter in fruits can be economically beneficial, since it reduces harvesting and transportation costs, and facilitates concentration of the product extract, as in canning tomatoes (Pasternak and De Malach, 1994).

Irrigating tomato with saline water for 2 weeks before the expected time of ripening increased the total soluble solids and citric acid content of the fruits by reducing the water content (Mizrahi and Pasternak, 1985). However, NaCl is not recommended as a soil additive due to the dispersive action of Na on soil clay particles. Applications of KCl about two weeks before harvest might improve tomato quality, but this can only be done in greenhouses or trickle irrigated fields because mechanical harvesting requires stopping other forms of irrigation one month before harvest.

4.2.2. Cucumber (*Cumumis sativus* L.)

The average K content in fresh cucumber fruits is 1.6 g kg^{-1} and about 32 g kg^{-1} on a dry weight basis (Geraldson, 1985). Adams (1982) suggested that analysis of the sap pressed from petioles might be used for a rapid and accurate assessment of the K status of mature fruiting cucumber plants. The K concentration in the petiole sap of healthy leaves is in the range of 3500-5000 g m^{-3}, and the corresponding K in the dried laminae is 25-54 g kg^{-1}. Lamrani *et al*. (1996) found that K acted positively on chlorophyll a and carotene levels with 11% and 7% increase compared with the control plants, respectively. Chlorophyll b did not vary significantly due to K application.

Cucumber is considered a salt sensitive crop (Maas and Hoffman, 1977; Jing *et al.*, 1992). The salinity threshold of cucumber is 1.7 dS m^{-1}, and each unit of increase in EC greater than the threshold results in 15.9% yield decrease (Maas and Hoffman, 1977). Visible salt injury symptoms in the hybrid *Pepinex* were observed at salinity levels of NaCl greater than 2.7 dS m^{-1}, when the Na and Cl content in the leaves exceeded 4.0 and 36 g kg^{-1} DW, respectively (Chartzoulakis, 1991). Salinity decreased the number of fruits, fruit size and delayed the harvest of the first fruit. However, salinity improved the fruit taste by increasing the content of soluble solids (Chartzoulakis, 1991).

4.3. Fruit trees

4.3.1. Citrus (*Citrus sp.* L.)

The role of K nutrition in citrus production was extensively reviewed by Erner *et al*. (1999). Citrus fruits remove quite large amounts of K from the soil every year. The amount may exceed 80 to 100 kg K ha^{-1} with large yields assuming a % K of 2 g kg^{-1} fresh fruits and fruit yield of 40 to 50 tons ha^{-1}. Intensive continuous cultivation of citrus requires K fertilizers on most soils, especially following years of large yield.

Visible leaf symptoms of K deficiency, such as leaf chlorosis, and its influence on vegetative growth do not appear until the trees are extremely deficient with leaf K content less than 2.5 g kg^{-1} of K (Koo, 1985). Most leaf K standards for citrus are based on 120 to 180 day-old spring flush leaves from non-fruiting bud terminals. The effect of fruit as a K sink on the K content in citrus leaves has also been documented (Koo, 1985). Increased fruit production from K fertilization has been reported up to leaf % K of about 15 to 17 g kg^{-1} (Chapman, 1982; Reese and Koo, 1975). However, the leaf % K is affected by a number of factors including leaf age, position on the twig, rootstock-scion combination, the size of the fruit yield and particularly the antagonistic effects among N, K, Ca and Mg (Koo, 1985) and the difference between fruiting and non-fruiting stem leaves (Smith, 1966). Annual leaf analysis is helpful to trace the trends in K requirements.

Citrus trees are generally sensitive to salt (Zekri, 1993). Large amounts of Cl accumulate in the leaves and in the fruit juice when trees are irrigated with water containing high Cl concentrations (Syvertsen *et al*., 1993). The Cl content of old mature leaves is much higher than that of young leaves (Bell *et al*., 1997a). The adverse effects of salinity in citrus leaves are caused by the accumulation of Cl and not by Na levels or water potential (Walker *et al*., 1982; Banuls and Primo-Millo, 1992; Banuls *et al*., 1997). For beneficial effects of Cl on the fruit yield of *Washington* navel oranges grafted on *Rough Lemon* rootstock, the concentration in the irrigation water should not exceed about 4.3 mM (Cole, 1985). Necrotic burn symptoms usually appear when the Cl level in mature leaves of orange citrus exceeds 15 g kg^{-1} DM (Romero and Syvertsen, 1996). Irrigation of a citrus orchard (annual application about 1100 mm) with water containing Cl at a concentration of 1.0-3.7 mM had almost no effect on soil salinity or leaf Cl concentration (Cole, 1985).

The degree of Cl damage to citrus trees varies with rootstock characteristics (Zekri, 1993). In mature leaves, the critical Cl level for the appearance of leaf toxic symptoms is between 2 g kg^{-1} (Cole, 1985) and 7 g kg^{-1} (Embleton *et al*., 1978). Analysis of the distribution of Cl in the whole plant showed that a Cl-tolerant rootstock prevents the transport of Cl from the roots to the leaves (Skene and Barlass, 1988). Bar *et al*. (1997) suggested that the relative tolerance of citrus root stock to Cl might be attributed both to their ability to restrict Cl uptake and transport to the leaves and to the ability of the leaf tissue to withstand high Cl concentrations.

The reduction in citrus growth caused by NaCl depends more on the identity of the scion than on that of the rootstock, whereas the opposite is true for defoliation (Banuls and Primo-Millo, 1995). Changes in the ionic content of leaves and roots indicated that the *Cleopatra* mandarin scion (Cl-tolerant) accumulated less Cl in the leaves than did *Troyer* citrange scions (Cl-sensitive), even when both were grafted on the same rootstock. Plants of *Ramsey*, irrespective of their origins, accumulated quite high levels of Cl in their petioles, despite the fact that this cultivar is noted for its ability to restrict Cl uptake under saline conditions. Leaf injury and defoliation were closely correlated with leaf % Cl (Skene and Barlass, 1988).

4.3.2. Kiwifruit (*Actinidia deliciosa*)

Large quantities of K are required annually to maintain high yields of quality kiwifruits (Smith *et al*., 1987). Fruit yields responded linearly when soil exchangeable K increased from 150 to 300 mg kg^{-1}, with yields ranging from 630 to 1620 g FW m^{-2} (Buwalda and Smith, 1991). The flower number per winter bud also increased significantly with increasing soil exchangeable K. Flower evocation in kiwifruit can be linked to growth and development of the vine in the previous season (Smith *et al*, 1987), so flowering is sensitive to the previous K nutrition. The soil K content did not significantly affect the mean fruit weight (109 g), so the effects of K on fruit number principally accounted for the yield differences (Buwalda and Smith, 1991). During the first 4 weeks after bud burst, leaf % K declined and was not significantly affected by the soil K content. Flowering and fruit yields were associated with differences in leaf K status only in the first 6 weeks after bud burst. Flower development is very sensitive to the K status in early spring (Buwalda and Smith, 1991). Initial K fertility and the form of K fertilizer applied did not affect fruit firmness after 120 days of cool storage.

Kiwifruit requires exceptionally high levels of Cl. Typically, the Cl concentration in the leaves of high-yielding kiwifruit vines exceeds 8 g kg^{-1} DM, and should be at least 2.1 g kg^{-1} in order to maintain healthy growth (Table 4.4; Smith *et al*., 1987). The symptom of Cl deficiency is the appearance of discrete patches of pale green chlorotic tissue between the main veins near the leaf tip (Smith *et al*., 1987). Only when leaf % Cl exceeded 15 g kg^{-1} DM, did the application of KCl induce leaf breakdown (marginal leaf scorch) followed by necrosis and leaf drop (Prasad *et al*., 1993).

Table 4.4. Effect of chloride on the chloride concentration in the youngest leaf and growth of kiwifruit.

Cl in nutrient solution (mM)	Cl in youngest leaf (g kg^{-1} DM)	Total dry matter (g plant^{-1})	Mean leaf area (m^2)
0	0.7	8	0.17
0.35	1.5	32	0.41
0.7	2.1	37	0.5
1.4	4	34	0.43

Based on Smith *et al*. (1987).

Kiwifruit is well adapted to the use of Cl rather than organic acid anions to balance the total cation charges in the leaf. Therefore, the anion accompanying K in the solution around plant roots can significantly influence K uptake. The influx of K in kiwifruit is limited when SO_4 rather than Cl is the anion accompanying the K. Both fruit yield and plant dry weight were significantly higher when Cl rather than SO_4 was the accompanying anion (Buwalda and Smith, 1991), and leaf levels of K tended to be lower when K_2SO_4 was used compared to KCl (Marsh *el al*., 1991).

4.3.3. Avocado (*Persea americana* Mill.)

In avocado, leaf % K is defined as: low, 3.5 to 7.4 g kg^{-1}; sufficient, 7.1 to 20.0 g kg^{-1}; and high, 21.0 to 30.0 g kg^{-1} on a dry weight basis (Jones *et al*., 1991). As shown in Fig. 3.16-C, leaf % K declines rapidly with flower development from late February to March. The older leaves from the previous season are active until March and then, two weeks later, juvenile leaves with large K content develop. Development of flowers and new leaves is simultaneous, both demanding large amounts of K. These processes occur in March in a Mediterranean climate, when the soil is still cold and root uptake of K is limited. Therefore, leaves and fruit must draw K from the trunk, root, and bark reserves (Bar and Glusman, 1991).

It is possible that the low level of K in leaves is responsible for the low yields of avocado despite its huge number of flowers. Avocados have between 1 and 1.5 million flowers per tree (Bar, personal communication) in trusses each containing 150-250 flowers and weighing about 1.7 g with a K concentration of 25g kg^{-1}. These data suggest that the amount of K that is in the trusses of one plant may approach 210-310 g just to satisfy the need for the trusses. Simple calculations such as this underline the importance of increasing the use of K for increasing avocado fruit yields.

Avocado is extremely sensitive to soil salinity. Chloride concentrations in the irrigation water, considered tolerable for many crops, are detrimental to avocado (Bingham *et al*., 1968). Foliar accumulation of Cl induces necrosis, early leaf shedding and decreased yield (Bingham *et al*., 1968).

Different rootstocks of avocado exhibit marked differences in leaf % Cl as well as in tolerance to Cl (Lahav *et al*., 1992). Increasing the Cl concentration in the nutrient solution resulted in an increase in Cl levels in the leaves, roots, cotyledons, bark and wood of both salt-tolerant *Degania-113* and salt-sensitive *Smith* rootstocks (Bar *et al*., 1997). The Cl tolerance of the rootstock *Degania-113* is not a result of reduced Cl accumulation in the leaves, but rather of three other properties: (1) the ability of the leaf tissue to withstand high Cl levels; (2) the capacity to shed its Cl loaded leaves prematurely, and (3) its great growth rate, enabling accelerated growth after leaf shedding.

Leaf shedding may be a way in which avocado adapts to high Cl (Bar *et al.*, 1997). Increasing NO_3 in the root zone of avocado can reduce Cl uptake and content in the leaf (Figure 3.10) (Bar *et al.*, 1997).

4.3.4. Grapevine (*Vitis vinifera* L. ssp. *vinifera*)

Potassium removal by grapes is about 7.49 mg vine^{-1} (Cahoon, 1985) and 7.7 g plant^{-1} (Conradie, 1981). The annual K loss varies from 45 to 144 kg ha^{-1} depending on cultivar, fruit yield level and soil K fertility (Cahoon, 1985). An example of K uptake and distribution during one growing cycle has been discussed in section 3.1.6.1 (Fig. 3.4.).

The documented response of grapevine to K include increases in winter hardiness, frost resistance, yield, soluble solids content, and vine vigor (Cahoon, 1985). Increasing K concentration in the petiole of grapevine increased K and pH in the fruit juice, and decreased the titratable acidity during storage. A close relationship was found between petiole K content and juice content before storage (Morris *et al.*, 1980).

Irrigation of grapevines with saline water increases the Cl concentration in the leaves and induces leaf damage. The severity of such damage and the decline in photosynthesis is proportional to the leaf Cl concentration (Stevens and Harvey, 1995). Certain rootstocks that exclude Cl from the leaf grow better under saline conditions (Downton, 1985).

Chloride concentrations in grapevine rootstocks were greatly reduced in scions grown under controlled Cl concentrations at constant osmotic potential (Bernstein *et al.*, 1969). The average shoots dry weight of *Sultana* scions grafted on to five rootstocks decreased by 10% and 20% when treated with water containing NaCl at 10 and 20 mM, respectively (Downton, 1985).

Exclusion of Cl in grapevines is inherited either as a polygenetic or as a monogenetic trait (Sykes, 1992). Rootstocks of grapes such as *Ramsey* can restrict the uptake and/or transport of Cl to the shoots, conferring salt tolerance on scions such as *Sultana* and resulting in larger yields than own-rooted vines at high salinity. The use of a Cl-excluding rootstock reduced leaf Cl by about 60% (Stevens and Harvey, 1995).

Chloride salinity applied before bud burst (Downton, 1985) or before flowering (Hawker and Walker, 1978) has much more drastic effects on shoot development and cane weight than when applied later. With applications of up to 465 kg K ha^{-1} to grapevines, KCl and K_2SO_4 produced the same yield response and quality of fruit juice (Cline and Bradt, 1980). Application of both KCl and K_2SO_4 under drip irrigation were equally effective in increasing petiole K levels and reducing visual foliar symptoms of K deficiency in *Thompson Seedless* vines (Christensen *et al.*, 1991).

4.3.5. Coconut palm (*Cocos nucifera* L.)

The coconut palm is highly responsive to K which increases drought and disease resistance, hastens maturity and increases fruit set and the number of harvested nuts (von Uexküll, 1985). A mature, more than 10-year-old coconut palm yielding 1.8 t ha^{-1} of copra removes between 90 and 130 kg K ha^{-1} in one year. The number of coconuts required to produce 1 kg of copra was 4.5 with adequate K nutrition and 8 where palms were under K stress.

The critical level of leaf % K is about 1 g kg^{-1} DM (von Uexküll and Sanden, 1986). Potassium deficient leaves show less organization in the mesophyll than healthy leaves and increased diameter of the adaxial fibers (Meerow and Broschat, 1991).

Potassium chloride is the most widely used fertilizer for both coconut and oil palms. It increases the size (weight) of the nuts and the copra yield, as well as the Cl and Ca concentration, but slightly decreases K in the leaves (von Uexküll and Sanders, 1986).

The use of NaCl and seawater is an ancient and very common practice among coconut growers in many parts of the world (Bonneaux *et al.*, 1997) and sufficient evidence supports the contribution of Cl to oil palm production. Palms contain little starch that can produce malate as the accompanying anion for K in their guard cells (von Uexküll and Sanders, 1986); therefore, Cl plays a vital role in stomatal movement. Healthy coconut palms along the seashore usually contain Cl at a concentration of 7-10 g kg^{-1} DM in their foliage. The optimal Cl concentration is usually in the range of 4.5-5.5 g kg^{-1}. At Cl concentrations lower than 2.5 g kg^{-1}, coconut palms may exhibit some visual symptoms of yellowing and/or orange mottling of the older leaves and the leaf tips and edges (von Uexküll and Sanders, 1986).

For example, the threshold value for EC in a soil extract is 4.5 dS m^{-1}. Above this level growth and copra yield begin to decline (Hassan and El-Samnoudi, 1993). No copra yield was obtained when the EC value of the soil extract exceeded 23.2 dS m^{-1}, and salinity symptoms appeared on the leaves, but the trees survived. Soil salinity leads to an accumulation of Cl, Na and K in the leaves, that of Cl was larger than that of Na and was highly correlated with salinity symptoms (Hassan and El-Samnoudi, 1993).

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