This effect appears to be associated with the ability of Ca to withdraw Cl from the xylem stream, particularly in the basal stem and roots. Comparison of the effects of the same concentration of KCl and $CaCl_2$ (Kafkafi *et al*., 1992) showed that inhibition of the influx of $^{13}NO_3$ in tomato and melon was caused by high Ca in the solution rather than by Cl. Decreasing the Na : Ca ratio under saline conditions had no effect on Cl concentrations in tomato or cucumber, but Cl concentrations were decreased in the roots and increased in the shoots (Al-Harbi, 1995). The Cl concentrations in cotton tended to decrease initially and then increase as the $CaCl_2$ concentration increased, but were largely unaffected by changes in external $CaCl_2$ (Gorham and Bridges, 1995).

Compared to SO_4 and NO_3, increasing the concentration of Cl from 3 mM to 13 mM stimulated Ca uptake by tomato, which decreased blossom end rot (BER) but caused more gold specks injury (Nukaya *et al*., 1991). Partial substitution of KNO_3 with KCl salts in culture solution also increased the gold specks (Hand and Fussell, 1995). It is not clear that why a large Cl supply resulted in greater Ca content in plants (De Kreij *et al*., 1992).

3.5. Plant positive responses to potassium and chloride

3.5.1. Yield response to potassium

The K requirement for optimal plant growth ranges from 20 to 50 g kg^{-1} dry weight in the vegetative organs, fleshy fruits, and tubers (Marschner, 1995; Fageria *et al*., 1991). The recommended amount of K for fruit tree are much less and most recommendations are still based on data from various sources that were published more than 50 years ago (Jones *et al*., 1991). For example, for apples (Chapman, 1966) the recommended foliar K concentrations in 1931 was 4.2-16.5 g kg^{-1} of leaf dry weight; by 1948 this was changed to 12-37 g kg^{-1}. For blueberries the recommended sufficiency K range was 1.0-1.5 g kg^{-1} of leaf dry matter in 1951 despite the fact that a shortage of K was associated with terminal growing point abortion (Cain and Eck, 1966).

Abundant information exists on the concentration of K in crop leaves but only limited information is available on leaf K in relation to time during the development of the reproductive organs, especially to final yields in fruit trees. The effects of fruiting or fruit load on foliar K concentrations are shown in Fig. 3.16. It is uncertain why foliar K levels for fruits, such as blueberry, grapefruit, orange and avocado, recommended by field advisors in some countries, are still very small (Table 3.4) despite the available information that suggests that much larger amounts of K are required.

Eck (1983) recommended an optimum K sufficiency range between 4.5 and 5.5g kg^{-1} for blueberry. However, these data were based on foliar samples taken one week after harvest. This is the period when foliar K is at a minimum and has little bearing on the true K status or requirement of the plant for maximum productivity. It is clear from the compiled data of Fageria *et al*. (1991) and Jones *et al*. (1991) (Table 3.4) that what is considered as the upper sufficiency limit for K for most fruit trees corresponds to the lowest levels for vegetables.

Table 3.4. Foliar K contents of fruit crops, vegetables, and other annual crops.

Name	K level (g kg^{-1} DM)			Name	K level (g kg^{-1} DM)		
	Deficient	Adequate	High		Deficient	Adequate	High
Fruits				Fruits			
Almond	10	14	14	Papaya	28	33	55
Apple	10	15	20	Peach	10	20	
Apricot	20	25	30	Pear	8	10	
Avocado	3.5	7.5	20	Pecan	8	12	
Banana	30	38	50	Pineapple	20	22	
Blueberry				Plum, Prune	10	16	
Highbush	3	5	9	Raspberry	10	15	
Rabbiteye	3.5	6	9	Walnut	9	12	
Cashew	7.2	8.9	14.4				
Cherry				Vegetables			
Sour	12	16	21	Garlic	30	39	
Sweet	15	25	30	Tomato	10	29	
Citrus	7	7--11	12--17	Watermelon	30	35	
Cranberry	4	8	8				
Currant	8	14	17	Annual crops			
Fig	7	9	10	Barley	20--28	23--41	
Grape	10	13	14	Common bean		15--35	
Grapefruit				Corn		20--25	
Nonfruiting	6	8	22	Cowpea		20--25	
Fruiting	6	8	22	Potato		35--65	
Hazelnut	4	7	24	Rice		29--35	
Lemon	7	10	20	Sorghum	15	15--20	20--30
Macadamia	4	5	10	Soybean	12	17--25	26--28
Mandarin	4.7	9	11	Sugarbeets	10		
Oil palm	16	17	19	Sugarcane		12--20	
Orange	4	7	11	Wheat	20--26	23--36	32--36

Based on Fageria *et al*. (1991) and Jones *et al*. (1991)

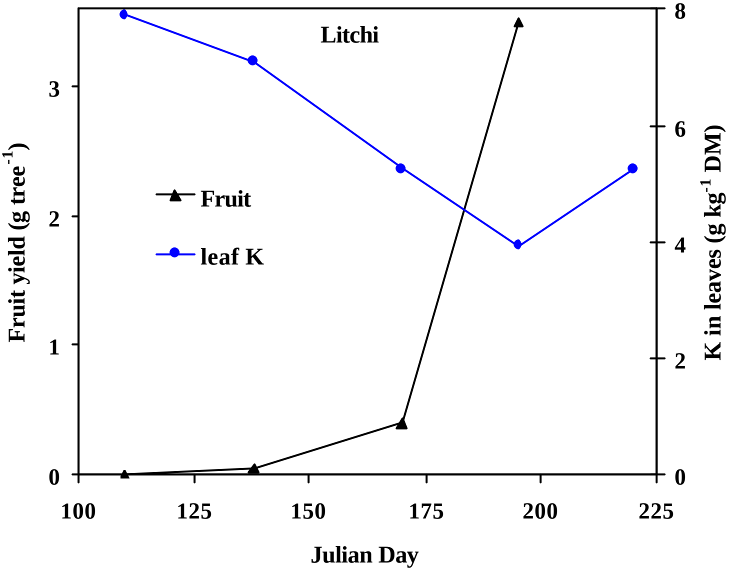


Fig. 3.16-A

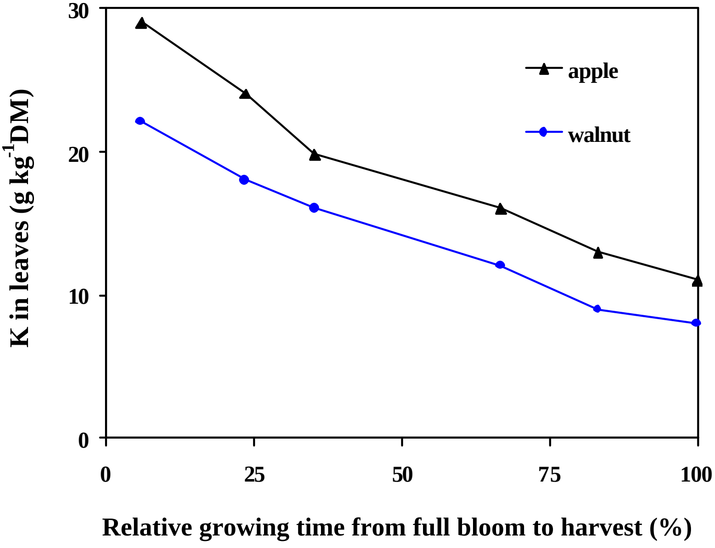


Fig. 3.16-B

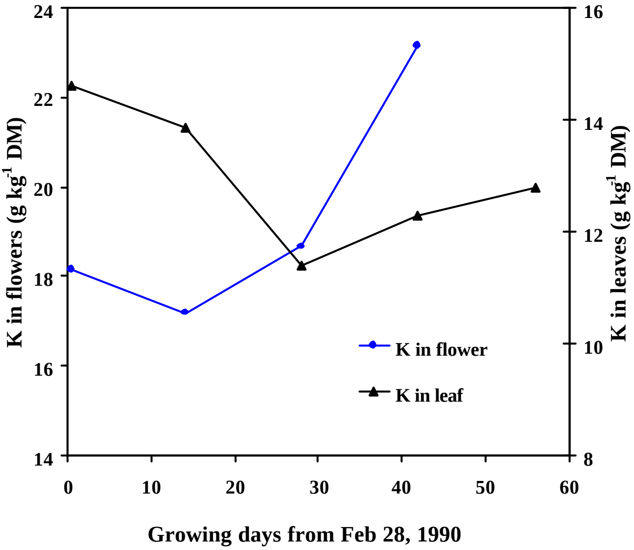


Fig. 3.16-C

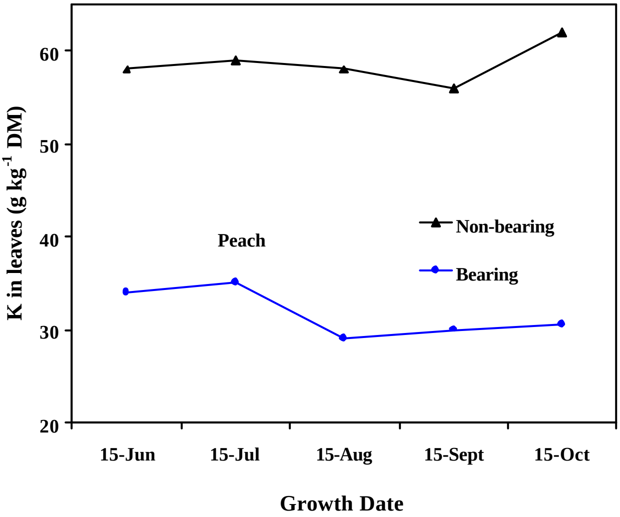


Fig. 3.16-D

Fig. 3.16. Potassium concentration in leaves during the reproductive stages of different fruit trees (Source: litchi and avocado: Bar and Glusman, 1991; apple: Cummings, 1985; walnut: Drosspoulos, 1996; peach: McClung and Lott, 1956).

Leigh and Wyn Jones (1984) considered a simple two-compartment model for K vacuole and cytoplasm. Potassium stored in the vacuole acts as a reserve pool which maintains the active cytoplasm K at a near constant level. If this model is correct, the concentration of K in the cytoplasm may be satisfied for the proper functioning of a large number of enzyme systems, while the fruit yield may be small. Low levels of mobile K in the vacuolar reserves can limit the flow of K to the developing fruit especially over short time periods. It seems reasonable that the K accumulated in mature leaves and stems at the start of fruit setting or grain filling should not only meet the K need of the developing fruits and seeds, as determined by final yield target, but also maintain the minimum K concentration needed for the biochemical functions in the cytoplasm in leaf cells.

3.5.2. Yield response to chloride

Chloride deficiencies in plants generally occur at inland sites (Fixen, 1987). Substantial responses to Cl containing fertilizers have been reported for different crops in many parts of the world: coconut (von Uexküll and Sanders, 1986), corn (Heckman, 1995), kiwifruit (Smith *et al*., 1987), oil palm (von Uexküll, 1990), potato (Gausman *et al*., 1958a), spring wheat and barley (Fixen *et al*., 1986; Engel *et al*., 1994), tobacco (Li *et al*., 1994), and sugar beet (Zhou and Zhang, 1992). The probability of Cl deficiency in field situations and thus response to Cl fertilization, increases in plant species with a high Cl requirement, such as wheat, sugar beet, kiwifruit, palm trees, and in highly leached soils with a low input of Cl from rain and other sources.

There is a wide range in the concentration of Cl at which deficiency in plants occurs. It varies between 0.13 g kg^{-1} for spinach and 5.7 g kg^{-1} for sugar beet (Table 3.5). In wheat, the Cl concentration of leaf tissue at heading is a good predictor of the response to Cl fertilization (Engel *et al*., 1998); the critical range is between 1.5 and 4 g kg^{-1} DM, above which no further response is expected (Fig. 3.17). The recommended application rate of Cl is 11.2-33.6 kg ha^{-1} when Cl deficiencies are suspected (Mortvedt *et al*., 1999).

In pot experiments, positive responses to Cl at 100-200 mg kg^{-1} soil were reported for white potato, peanut, tomato and young may trees, and at 100-1600 mg kg^{-1} soil for sugar beet (Jing *et al*., 1992). On a sandy loam soil, Cl applications of up to 400 kg ha^{-1} yielded 500-1500 kg ha^{-1} more corn grain than was obtained in the control (Heckman, 1995). Grain yields of corn were positively correlated with increases in Cl concentrations in the leaves. In wheat, there was no yield response to Cl fertilization when the Cl content was above 70 kg ha^{-1} in the top 12 cm of soil (Fixen *et al*., 1987).

Yield increases from Cl supplied as KCl, $CaCl_2$, NH_4Cl and NaCl have also been associated with suppression of foliar or root diseases of wheat (Christensen *et al*., 1981; Engel *et al*., 1997).

Table 3.5. Chloride concentration in plants.

			Concentration ranges in various tissue Cl (g kg^{-1} DM)			
Crop	Latin name	Plant part	Deficient	Normal	Toxicity[a]	References
Alfalfa	*Medicago sativa* L.	Shoot	0.65	0.9-2.7	6.1	Ozanne *et al*., 1957; Eaton, 1966
Apple	*Malus domestica*	Leaves	0.1		>2.1	Eaton, 1966
Avocado	*Persea americana* Mill.	Leaves		~1.5 - 4.0	~7.0	Bar *et al*., 1997; Lahav *et al*., 1992
Barley	*Hordeum vulgare* L.	Heading shoot	1.2 - 4.0	>4.0		Engel *et al*., 1994; 1997
Citrus	*Citrus sp.* L.	Leaves		~2.0	~4.0 - 7.0	Bell *et al*., 1997a; Bar *et al*., 1997
Coconut palm	*Cocos nucifera* L.	Leaves	2.5 - 4.5	>6.0 - 7.0		von Uexkull and Sanders, 1986
Corn	*Zea mays* L.	Ear leaves		1.1 - 10.0	>32.7	Parker *et al*., 1985
Corn	*Zea mays* L.	Shoots	0.05 - 0.11			Johnson *et al*., 1957
Cotton	*Gossypium hirsutum* L.	Leaves		10.0 - 25.0	>25.0 - 33.1	Tan and Shen, 1993
Grapevine	*Vitis vinifera* L. ssp. *vinifera*	Petioles		0.7-8.0	10.0-11.0	Downton, 1985; Eaton, 1966
Kiwifruit	*Actinidia deliciosa*	Leaves	2.1	6.0 - 13.0	>15.0	Smith *et al*., 1987; Prasad *et al*., 1993
Lettuce	*Lactuca sativa* L.	Leaves	>0.14	2.8 - 19.8	>23.0	Johnson *et al*., 1957; Wei *et al*., 1989
Pear	*Pyrus communis*	Leaves		<0.50	>10.0	Robinson, 1986
Peach	*Prunus persica*	Leaves		0.9-3.9	10.0-16.0	Robinson, 1986; Eaton, 1966
Groundnut	*Arachis hypogaea* L.	Shoot		<3.9	>4.6	Wang *et al*., 1989
Potato	*Solanum tuberosum* L.	Mature shoot	<1.0	2.0-3.3	12.2	Corbett and Gausman, 1960
Potato	*Solanum tuberosum* L.	Petioles	0.71 - 1.42	18.0	44.8	James *et al*., 1970; Bernstein *et al*., 1951
Red clover	*Trifolium pratense* L.	Shoot	0.15 - 0.21			Whitehead, 1985
Rice	*Oryza sativa* L.	Shoot	<3.0		>7.0 - 8.0	Yin *et al*., 1989
Rice	*Oryza sativa* L.	Mature straw		5.1 - 10.0	>13.6	Huang *et al*., 1995; Zhu and Yu, 1991
Soybean	*Glycine max* L. Merr.	Leaves		0.3 - 1.5	16.7 - 24.3	Parker *et al*., 1986; Yang and Blanchar, 1993
Spinach	*Spinacia oleracea* L.	Shoot	>0.13			Robinson and Downton, 1984
Spring wheat	*Triticum aestivum* L.	Heading shoot	1.5	3.7 - 4.7	>7.0	Fixen *et al*., 1986; Wang *et al*., 1989
Strawberry	*Fragaria vesca*	Shoot		1.0 - 5.0	>5.3	Wang *et al*., 1989; Robinson, 1986
Subterranean clover	*Trifolium subterraneum* L.	Shoot	>1.0			Ozanne *et al*., 1957; 1958
Sugarbeet	*Beta vulgaris* L.	Leaves	0.71 - 1.78			Ulrich and Ohki, 1956; Terry, 1977
Sugarbeet	*Beta vulgaris* L.	Petioles	<5.7	>7.1 - 7.2	>50.8	Ulrich & Ohki, 1956; Zhou & Zhang, 1992
Tobacco	*Nicotiana tabacum* L.	Leaves		1.2 - 10.0	>10.0	Li *et al*., 1994; Eaton, 1966
Tomato	*Lycopersicon esculentum* Mill	Shoot	0.25		~30.0	Broyer *et al*., 1954; Kafkafi *et al*., 1982
Wheat	*Triticum aestivum* L.	Heading shoot	1.2 - 4.0	>4.0		Engel *et al*., 1994; 1997

[a] The plant yield declines or the plant shows visible scorching symptoms in leaves.

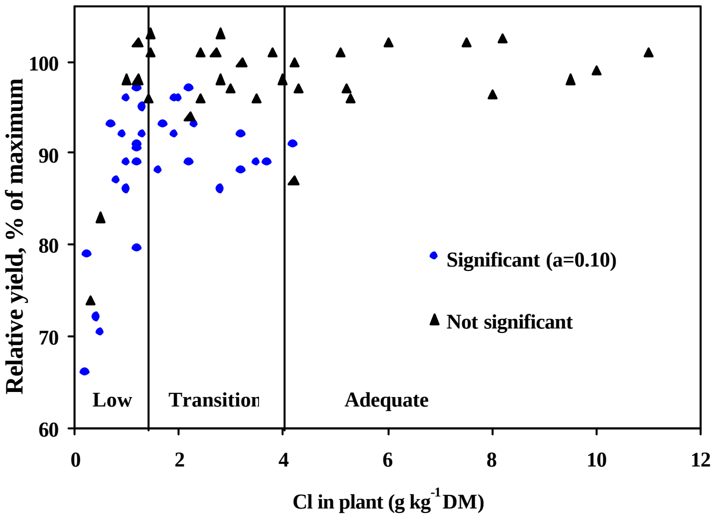


Fig. 3.17. Relationship between the chloride concentration in the whole plant and the relative grain yield of wheat and barley cultivars known to be chloride responsive. US Great Plains, 1982-1990 (Source: Engel *et al*., 1992).

Ammonium chloride produced yields of rice that were equal to or larger than those obtained with urea and ammonium sulphate. In a glasshouse experiment rice yields with NH_4Cl were significantly lower than with $(NH_4)_2SO_4$, especially at high salinity levels (Meelu *et al*., 1990). With NH_4Cl sugar cane yields exceeded or equalled those given by $(NH_4)_2SO_4$ at 67-225 kg N ha^{-1} (about 170-570 kg Cl ha^{-1}) (Vede Narayanan, 1990).

3.5.3. Deficiency symptoms of potassium and chloride

3.5.3.1. Potassium

The relative growth rate of plants is correlated with K transport from root to the shoot (Pitman and Cram, 1977) and distribution and redistribution in the plant are facilitated by the high mobility of K in the plant. Therefore, an inadequate supply of K to plants can be diagnosed visually. Growth, defined as the irreversible increase of cellular volume by cell division and cell extension, involves a requirement for K to maintain the osmotic potential of cells (Wyn Jones *et al*., 1979). The importance of K in turgor pressure dependent growth has been demonstrated for cotton fiber (Dhindsa *et al*., 1975) and the bean plant (Mengel and Arneke, 1982).

As a consequence of reduced turgor, leaves of K-deficient plants quickly become flaccid when suffering from water stress. Under conditions of slight

K deficiency leaves often become dark green or blue-green, a color change perhaps related to greater densities of chloroplasts in K smaller, deficient cells (Marschner and Possingham, 1975). The dark to bluish green leaves symptom has been observed in many species: rape, potatoes, tomatoes, lettuce, cucumbers, peas, beans, cauliflower, tobacco, sugarcane, tea, apple and some other crops (Bergmann, 1992). A metallic bronze shine is also observed. Bergmann (1992) collected wide color pictures showing K deficiency symptoms in different crops. When deficiency is severe the chloroplasts are destroyed. The typical development of K deficiency symptoms starts with the collapse of single leaf cells and develops to spots of necrotic tissue as well as necrosis of leaf tips and margins. Marginal and interveinal chlorosis precedes cell degeneration in summer rape (Beringer and Nothdurft, 1985). Necrotic margins on older leaves indicate some leaf structural changes, and lodging of cereals suggesting insufficient stability of stalk sclerenchymatic tissues (Beringer and Nothdurft, 1985). The interpretation of such deficiency symptoms therefore needs more detailed consideration.

As has been observed with other nutrients, K deficiency symptoms are dependent on species and growing conditions. Chlorosis and necrosis are generally first observed in the older leaves. Potassium seems to be preferably exported from leaves with high metabolic activity to new growing organs (Beringer and Nothdurft, 1985). In K deficient plants the length of stem internodes as well as stem diameter are reduced (Wakhloo, 1975) due to reduced activity of the cambium. Sclerenchyma fiber cells and woody parenchyma cells in the stems of K deficient plants form thin and poorly lignified cell walls. Therefore, K deficient plants have less mechanical strength, which renders them susceptibility to lodging.

The visual symptom of K deficiency in cotton is *cotton rust*, a yellowish white mottling on the leaf that begins on older leaves (Kerby and Adams, 1985). In potatoes, the older leaves turn dark to bluish-green, sometimes with a metallic bronze shine, and have a scorched appearance (Bergmann, 1992) (Plate 3.2).

3.5.3.2. Chloride

Physiological Cl deficiency symptoms in plants grown in nutrient solutions have been well characterized. Typical symptoms of Cl deficiency include wilting of leaves, curling of leaflets, bronzing and chlorosis similar, to those seen with Mn deficiency, and severe inhibition of root growth (Ozanne *et al*., 1957; Smith *et al*., 1987). A prominent symptom is restricted root growth with stubby, club-tipped or swelling lateral branches because Cl deficiency impaires cell division and extension. Such symptoms were found in tomato and lettuce (Johnson, 1957), spinach (Robinson and Downton, 1984), and kiwifruit (Smith *et al*., 1987). Chloride deficiency causes wilting of the leaflet blade tips, followed progressively by chlorosis, bronzing and necrosis in tomato (Broyer *et al.*, 1954). Other observed Cl deficiency symptoms included the developing of small yellowish spots with interveinal greener areas, premature wilting or curl of the leaf tips and margins, smaller, narrower and wrinkled leaves, as demonstrated in kiwifruit (Smith *et al.*, 1987), spinach (Robinson and Downton, 1984), sugarbeet (Terry, 1977), coconut palm (von Uexküll and Sanders, 1986), alfafa and cabbage (Johnson, 1957). The most distinctive symptom of Cl deficiency in barley was general chlorosis of newly emerging leaves, identical symptoms to those of Cl deficiency in cabbage (Johnson, 1957).

Chloride deficiency symptoms of plants are usually difficult to observe in the field unless a comparison can be made between plants with and without a deficiency. In cereal crops, restricted and highly branched root systems due to chloride deficiency are found. Chloride deficiency is associated with delayed maturity, smaller kernel size and increased tendency for lodging (Mortvedt *et al.*, 1999). A leaf spot complex (*physiological leaf spot*) that results in tissue necrosis in wheat has been identified as a visible symptom of Cl nutritional deficiency (Mortvedt *et al.*, 1999; Engel *et al.*, 1998) (Plate 3.3).

Adequate Cl increases stem diameter, flag leaf area and head size in small grain crops, such as wheat and barley (Fixen, 1993). Chloride fertilization has advanced spring wheat development by as much as 1 to 4 days and winter wheat development by as much as 5 to 7 days in the U.S. Great Plains (Fixen, 1993). Chloride deficient coconut palm had reduced growth rates, fewer nuts set, reduced nut size, droopy leaves, signs of moisture stress, and stem cracking and bleeding (von Uexküll and Sanders, 1986).

3.6. Crop sensitivity to chloride

3.6.1. Effects on yield

Sensitivity to high Cl concentrations varies widely between plant species and cultivars. Generally, many woody plant species and beans are susceptible to Cl toxicity, whereas most non-woody crops tolerate excessive levels of Cl (Maas, 1986). The critical Cl toxicity concentration is about 4-7 g kg^{-1} and 15-50 g kg^{-1} for sensitive and tolerant plant species, respectively (Table 3.5). For the navel orange cv. *Washington* grafted on a poor chloride excluder rootstock, *Rough Lemon*, when the Cl in the leaf exceeds 2 g kg^{-1}, the fruit yield declines linearly with increasing leaf Cl concentration (Fig. 3.18). However, mature leaves of citrus were able to tolerate Cl concentrations of up to 350 mM in leaf tissue water or approximately 25 g kg^{-1} DM under glasshouse conditions without sustaining permanent damage to the photosynthetic system (Walker *et al.*, 1982). Certain soybean varieties in the southern U.S. are effected detrimentally by the problem can be corrected by changing varieties (Parker *et al.*, 1983).

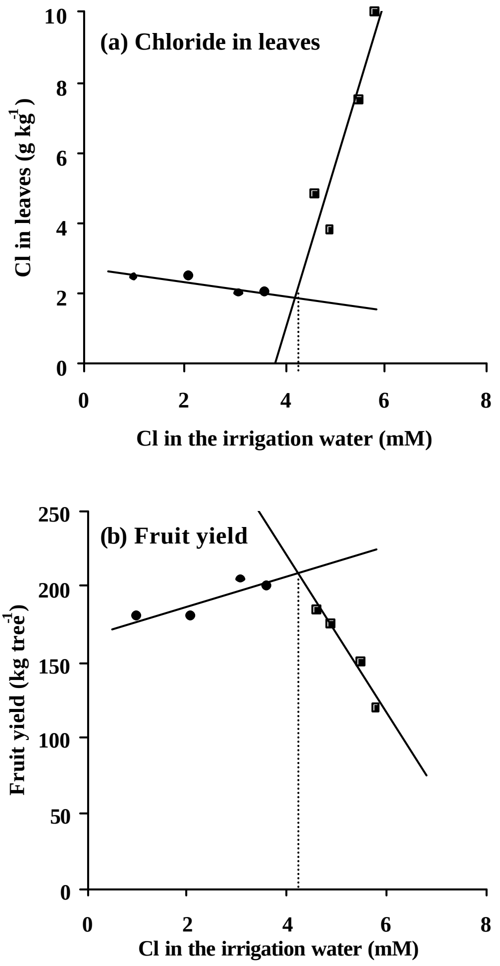


Fig. 3.18. Effect of chloride concentration in the irrigation water on chloride concentration in leaves (a) and on fruit yield (b) of orange (Source: Cole, 1985).

The order of tolerance of common agricultural crops to chloride (Table 3.6) is very similar to the order of the critical electrical conductivity (EC) values of saturated soil extracts. The crop with the greatest tolerance to chloride is sugar beet which may contain up to 50.8 g Cl kg^{-1} in the leaves (Zhou and Zhang, 1992). Chinese cabbage, on the other hand, is sensitive to Cl; when the Cl level in the irrigation water reached 80 g m^{-3}, the dry matter percentage was significantly decreased (Yin *et al.*, 1989).

Table 3.6. Critical toxicity concentrations of chloride and ECe values in soil and in saturated soil extracts, listed in order of increasing tolerance to chloride.

	Critical toxicity concentration		
Crop	Cl (mM)[a]	EC_e (dS m^{-1})[b]	mg Cl kg^{-1} soil[c]
Strawberry	10	1.0	250
Bean	10	1.0	
Onion	10	1.2	
Carrot	10	1.0	
Radish	10	1.2	
Lettuce	10	1.3	100
Turnip	10	0.9	
Pepper	15	1.5	
Apple		1.7	250
Sweet potato	15	1.5	300
Grape		1.8	400
Corn	15	1.7	800
Flax	15	1.7	500
Potato	15	1.7	500
Broadbean	15	1.5	
Sugarcane	15	1.7	
Cabbage	15	1.8	500
Spinach	20	2.0	
Cucumber	25	2.5	600
Tomato	25	2.5	600
Broccoli	25	2.8	
Sugarbeet	40	4.0	3200
Cowpea	50	1.3	
Wheat	60		600
Sorghum	70	6.8	700
Sugarbeet	70	7.0	1600
Cotton	75	7.7	1600[d]
Barley	80		

[a, b, c] Selected and recompiled from Maas (1986), Ayers and Wescott (1985) and Jing *et al*. (1992), respectively.

[a] Maximum Cl concentration in saturated soil extracts without loss in yield

[b] Maximum ECe value in saturated soil extracts without loss in yield

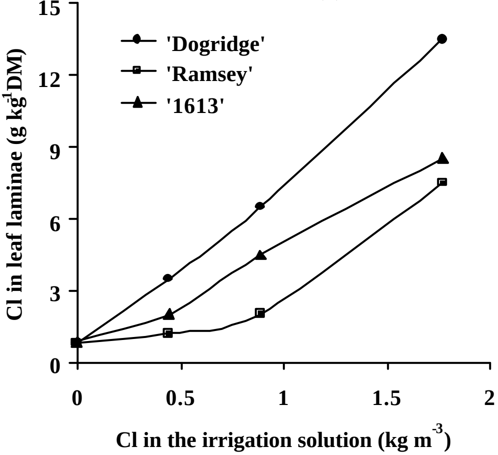
[c] Maximum soil Cl concentration above which yield decline to 95% of the maximum yield is observed

[d] From Tan and Shen (1993).

Corn is tolerant to high levels of soil Cl, but soybean is sensitive (Parker *et al.*, 1983; 1985). At soil Cl levels of 100-200 mg kg^{-1}, even sensitive crops such as sweet potato, white potato, sugarcane and tobacco showed no negative effects in yield or quality (Jing *et al.*, 1992).

The tolerance of a crop to Cl is not directly related to the concentration in the plant tissues as is shown for different varieties of grapevine (Fig. 3.19).

(a) Chloride



(b) Cane dry matter

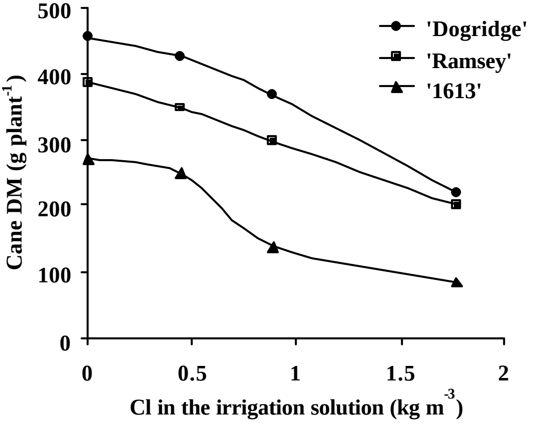


Fig. 3.19. Effect of chloride in irrigation water on leaf lamina chloride concentration (a) and cane dry matter (b) of *Sultana* grapevine scion grafted on three rootstocks (Recalculated and redrawn from Downton, 1985).

Scions on *Dogridge* rootstock contained the highest leaf Cl concentration but exhibited the greatest growth and were the least affected by salinity (Downton, 1985). There was no relationship between the amount of chloride in different plant parts and cane weight. Similar findings were reported by Skene and Barlass (1988) for two rootstocks of grapevine. Dry matter yields of the whole plant and Cl levels in the leaves of the salt tolerant avocado cultivar *Degania-113* were higher than in the salt-sensitive cultivar *Smith* (Bar *et al*., 1997). A salt tolerant alfalfa variety accumulated considerably higher concentrations of Na and Cl than did the salt-sensitive variety (Ashraf and O'Leary, 1994). The salt-tolerant and salt-sensitive accessions of safflower did not differ in tissue Cl, K or Ca (Ashraf and Fatima, 1995). It seems likely that factors associated with vigorous growth or Cl compartmentation within the cell could offset the inhibitory effects of Cl accumulation. The level of accumulated Cl in the plant should therefore not be considered as the sole criterion of crop tolerance to Cl.

Plants are generally more tolerant of soil salinity during cooler seasons than in warmer ones (Pasternak and De-Malach, 1995). Berry, citrus, vegetable, conifer and ornamental plants show varying degrees of tolerance to Cl, particularly in the seedling stage. The salt tolerance of citrus rootstock varies with the stage of seedling development (Zekri, 1993). Cucumber is more salt tolerant during germination than during the vegetative or fruiting stages (Chartzoulakis, 1991).

3.6.2. Symptoms of excess chloride

Compared with Cl deficiency, the effect on crops of Cl excess in the field is relatively common. The typical symptoms of excess Cl in woody plants are premature yellowing of leaves, burning of leaf tips and margins and bronzing followed by abscission of leaves at high levels of Cl. Chloride toxicity symptoms in soybean appear on older leaves during vegetative growth, especially at the stage from flowering to pod developing, and progress upwards through the plant until the entire foliage is affected (Parker *et al*., 1986). The most striking symptom is that older leaves turn yellow followed by drying and curling, scorching and defoliation (Parker *et al*., 1983). Chloride toxicity symptoms are more severe under drought stress.

The degree of damage caused by excess Cl is influenced both by rootstock and by nitrate as demonstrated in avocado. For example, in *Ettinger* avocado plants grown on the *Mexican* rootstock, the Cl toxicity symptoms appeared mainly in the leaves and shoots with almost no effect on the roots, whereas the main toxic influence of Cl on the *West Indian* rootstock, appeared in the root system, with reduced root weight and increased shoot/root ratios (Wiesman, 1995).

Chloride toxicity in plants is often hard to diagnose for two reasons: (1) it is difficult to separate the effects of Cl from those of any accompanying cation, commonly Na; and (2) it is difficult to distinguish between the specific toxic effects of ions and the cellular dehydration caused by their excessive external concentrations. Visual symptoms of marginal leaf necrosis due to Cl accumulation such as those seen in avocado might be misleading, as similar symptoms in mango (Plate 3.4) are the result of iron deficiency (Xu *et al*., 1999b). Citrus sensitive plants shed their leaves when exposed to salts but do not exhibit leaf necrosis (Bar *et al*., 1997).

3.7. Potassium chloride and crop quality

3.7.1. Potassium and crop quality

Potassium has been described as the *quality element* for crop production (Usherwood, 1985). Potassium functions in photosynthesis, respiration, assimilate translocation, as well as in numerous enzyme systems which results in great influences both on growth and on the quality of the marketable plant parts and fruits. The influence of K on quality can also be indirect as a result of its positive interaction with other nutrients and production practices. However, quality varies with the crop, the plant part to be marketed and the intended use, therefore, standards for comparison are needed to evaluate the role of K on quality.

Potassium promotes N absorption, stimulating amino acid translocation from vegetative shoot to the grain that favors the synthesis of gluten and prolamine (Mengel *et al*., 1981), as well as the formation of proteins that improve baking quality (Usherwood, 1985). Potassium application increases the starch content of rice, wheat (Kemmler, 1983), corn (Raja, 1972), soybean (Jeffers *et al*., 1982), sesame (Mitchell *et al*., 1976) and some forage crops (Usherwood, 1985).

The positive effect of K on the oil content of crops has been reported for sesame, soybean, rape and cotton seeds (Usherwood, 1985; Weber, 1985). In India, applying K increased the oil percent in groundnut by 1-2% (Weber, 1985; Golakyia, 1999).

Potassium application not only increased the K content of orchard grass but also increased protein N and decreased non protein N, producing higher digestible dry matter and protein yields of corn silage (Keeney *et al*., 1967, cited by Usherwood, 1985). This resulted in an improved feeding value of the forage for livestock.

Recent experiments in India showed that applying K to potatoes significantly increased both true protein and vitamin C contents, and in addition, increased the yield of large and medium size tubers and decreased weight loss from the tubers after harvest (Imas, 1999). Potassium deficiency causes accumulation of reducing sugars and decreases the starch content in potato tubers, thus producing dark colored chips (Perrenoud, 1983). Internal blackening of potato tubers may be related to a high content of tyrosine caused by K deficiency.

Potassium application increased boll size of cotton, improved micronaire value, fiber strength, and fiber length and increased the percentage of mature fibers (Cassman *et al.*, 1990). They concluded that K supply to the cotton fruit was an important determinant of fiber quality under field conditions and that the K requirement for producing a high lint yield with acceptable quality could differ among genotypes. Pettigrew and Meredith (1997) further observed that K deficiency of cotton reduced the assimilation capacity associated with decreased lint yield and poorer fiber quality.

In citrus, K nutrition positively influences the size of fruit, thickness of the rind, and fruit color. The improved yield is due, in part, to reduced fruit fall from the tree and larger fruit size. Potassium also improves the citric and ascorbic acid (vitamin C) content of the juice, and other juice characteristics, like the acid/sugar ratio and soluble solids content (Koo, 1985).

With proper K nutrition, tomato fruit is generally higher in total solids, sugars, acids, carotene, and lycopene, as well as shelf life quality (Usherwood, 1985). A large amount of K is needed to achieve not only the largest fruit yield but also the greatest percentage of fruit suitable for marketing of tomato (Usherwood, 1985) and of papaya (Awada and Long, 1980).

Incidences of some physiological disorders of tomatoes, such as *gold specks*, *puffiness*, *blotchy ripening complex*, *grey wall* and *greenback* or *yellow shoulder*, can be reduced by applying large amounts of K (Kinet and Peet, 1997). In a survey of 140 processing tomato fields in central California, the incidence of the colour disorders *yellow shoulder* and *internal white tissue*, was negatively correlated with K status of both soil and plant (Hartz *et al.*, 1999).

Physiological disorders of citrus fruits like *plugging* and *creasing* are associated with high N and low K availability. Potassium deficiency resulting in small, thin-skinned fruit promotes fruit splitting, even though extra K will not always correct normal splitting in susceptible cultivars (Tucker *et al.*, 1994).

Often the amount of K required for optimum yield is also sufficient to secure good quality. However, the need of K to enhance fruit quality, as in citrus (Koo, 1985), is probably more critical than other aspects of yield production. In certain crops, quality is more important than yield to secure best economic return. In such cases more K is needed to ensure quality than is needed for maximum yield. Such is the case for banana (Lahav and Turner, 1983), cotton (Cassman *et al.*, 1990), potato (Wiebel, 1997), tobacco (Colyer and Pohlman, 1971), turf (Schery, 1968), ornamentals and some food crops (Usherwood, 1985).

The effects of K on shelf life are predominantly favorable, both through slowing senescence and through a decrease of numerous physiological diseases (Martin-Prevel, 1989). Potassium enhances storage and shipping quality of bananas, tomatoes, potatoes, onions and many other crops, and also extends their shelf life (Usherwood, 1985; Geraldson, 1985; Koo, 1985; von Uexküll, 1985; Martin-Prevel, 1989; Perrenoud, 1993).

Low K nutrition of bananas results in thin and fragile bunches with shorter shelf life (von Uexküll, 1985). Quality of citrus fruits during storage is also influenced by the K nutrition of the tree: the incidence of stem-end rot (*Diplodia natalensis*) and green mold (*Penicillium digitatum*) decreased as K application increased, therefore fruit loss during transport was reduced and shelf life in the supermarket increased (Koo, 1985). For potatoes, applying K reduced storage losses, and this was related to a reduction in the activity of catalase and peroxidase enzymes (Perrenoud, 1983).

3.7.2. Chloride and crop quality

Salinity improves both fruit taste and appearance quality of tomatoes and melons (Mizrahi, 1982; Mizrahi and Pasternak 1985; Faiz *et al.*, 1994). This phenomenon is attributed to the significantly higher content of total soluble solids and of aromatic and other components found in these fruits under saline conditions (Fig. 3.20; Davies and Hobson, 1981).

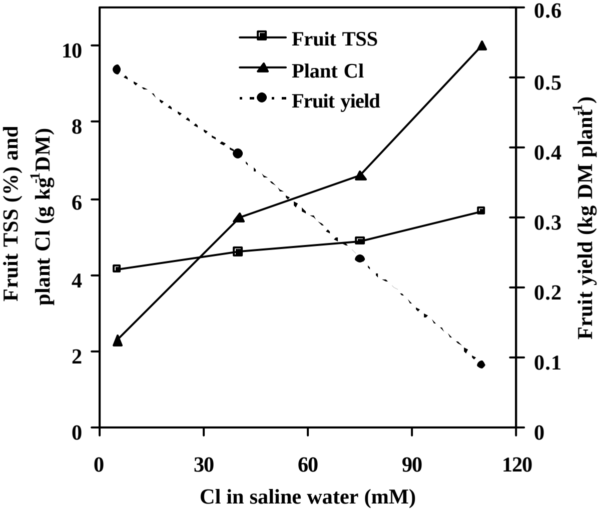


Fig. 3.20. Effect of chloride concentration in saline water on fruit yield, total soluble solids (TSS) of fruits and chloride concentration of tomato plant (Source: Feigin *et al.*, 1987).

Tomato juice quality was improved when plants were grown in saline solutions with an osmotic potential of approx. -0.45 MPa; because of greater acidity and an increase in total suspended solids and ascorbic acid (Albu Yaron *et al.*, 1993).

Most of the reported salinity effects are probably due to both Na and Cl. The specific influence of Cl on the quality of agricultural products is not clear. Wang *et al.* (1989) found that the soluble sugar and vitamin C contents were significantly higher in strawberries grown in soil containing Cl at 100-200 mg kg^{-1} soil than in soil containing 37 mg Cl kg^{-1} soil.

Chloride generally accumulates in the vegetative parts, mainly in the leaves (Fig. 3.21) of cotton, lettuce (Wei *et al.*, 1989), wheat, soybean and rice (Pan *et al.*, 1991b). The Cl content of grain, fruits and seeds is very low and is hardly affected by the Cl concentration of the soil solution. The concentration of Cl in sugar beet leaves increased from 9.8 to 54.1 g kg^{-1} with Cl fertilization, while the concentration in the roots was only 1.5 to 1.6 g kg^{-1}. The sugar content of the roots was not affected by the Cl application (Zhou and Zhang, 1992). Cotton seeds maintained a Cl concentration in the range 0.48-0.59 mg g^{-1} DM and the lint length was constant in the range of 28-29 mm when Cl application was increased up to 3200 mg kg^{-1} soil (Tan and Shen, 1993). Addition of KCl or $CaCl_2$ to soybean cv. *Essex*, a Cl accumulator, increased the Cl concentration in the seeds, but had no significant effect on the oil and protein content (Yang and Blanchar, 1993). There were no negative and even some positive effects of Cl salinity on grain quality of corn, sorghum, rice, spiked millet and wheat when Cl was applied at a rate of up to 800 mg kg^{-1} soil (Wang *et al.*, 1989; Jing *et al.*, 1992).

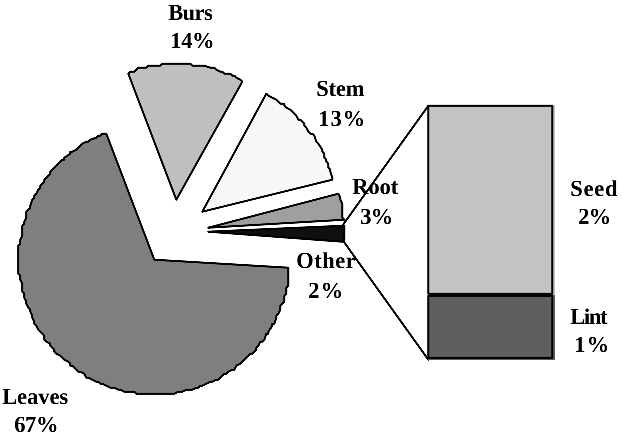


Fig. 3.21. Distribution of chloride in the different organs of cotton at the boll-opening stage (Redrawn from Tan and Shen, 1993).

The quality of leafy vegetables is relatively sensitive to Cl. Whereas the total fresh weight of Chinese cabbage was not affected when the Cl content of the irrigation water was less than 150 g m^{-3}, the dry weight and especially its vitamin C content were markedly reduced (Yin *et al*., 1989). Both the soluble sugar and the vitamin C content of lettuce decreased significantly when soil Cl application was above 100 mg kg^{-1} (Wei *et al*, 1989). In tobacco, good leaf quality was maintained as long as the amount of Cl in the soil was less than 72-107 mg kg^{-1} and the leaf Cl content was below 10 mg g^{-1} (Li *et al*., 1994). The effects of Cl on crop quality depend mainly on the marketed plant part. Fruit quality is generally more tolerant to high chloride than fresh leaf yield.

3.8. Potassium chloride and suppression of diseases and stresses

3.8.1. Potassium

3.8.1.1. Diseases

The role of K in crop resistance to diseases was extensively reviewed by Perrenoud (1990) (Table 3.7). In general, an inverse relationship is found between available soil K and the severity of disease caused by bacteria and fungi. It is a common practice to add K fertilizers to reduce certain diseases (Perrenoud, 1990). At low K levels (0.5 mM, 19.6 g m^{-3}) in culture solution, the incidence of Tikka leaf spot (*Cercospora archidicola Hori.*) on groundnut averaged 56%, but decreased to 11% at 3.0 mM of K (Umar *et al*., 1997). Leaf spot disease in cotton (small brown lesions caused by *Cercospora, Alternaria* and *Stemphylium*) is related to low soil K, low plant tissue K and/or low petiole K (Harris, 1997). Different K fertilizers (KCl, KNO_3, K_2SO_4, KH_2PO_4 and K_2HPO_4), applied as foliar sprays, were highly effective inducers of systemic protection against powdery mildew (*Sphaerotheca fuliginea*) in cucumbers (Reuveni *et al*., 1995).

Table 3.7. Influences of potassium application on disease severity caused by different pathogens.

Pathogen category	Number of observations of disease incidence[a)] Total	 Decreased	 Unchanged	 Increased
Bacteria	144	99 (69)	14 (10)	31 (21)
Fungi	1549	1080 (70)	112 (7)	357 (23)
Viruses	186	76 (41)	14 (7)	96 (52)
Nematodes	111	37 (33)	4 (4)	70 (63)

[a)] Percentage of total parentheses.

Source: Perrenoud (1990).

Potassium deficiency in late-season soybeans can lead to reduced yields and poor seed quality caused by pod and stem blight (*Diaphorte sojae* L.) and purple seed stain (*Cercospora kikuchii* L.) (Snyder and Ashlock, 1996). The application of K on a soil low in available K greatly reduced stem blight and purple seed stain (Camper and Lutz, 1977).

In potatoes, K fertilization was found to decrease the incidence on several diseases, such as late blight (*Phytophtora infestants*), dry rot (*Fusarium ssp.*), powdery scab (*Spongospora subterranea*) and early blight (*Alternaria solanii*) (Perrenoud, 1990; Marschner, 1995).

The intricate relationship between K nutrition and metabolic functions and growth, as well as its interrelationship with various other nutrients within the plant and the soil, provide ample opportunity for K to modify disease resistance or susceptibility. Potassium probably exerts its greatest effects on disease through specific metabolic functions that alter compatibility relationships of the host-parasite environment. For example, inorganic N accumulates in tracheal sap of K deficient corn plants through the impairment of N metabolism, which provides a more favorable environment for bacterial growth, and subsequent susceptibility to *Stewart*s wilt (McNew and Spencer, 1939). In the field, increasing N rates enhanced severity of corn smut (*Ustilago maydis*), while applying K suppressed its incidence by 19.6% (Kostandi and Soliman, 1997). An increase in the N or P content of oilseed rape plant was associated with an increase in the severity of black spot disease (*Alternaria brassicae*), whereas an increase in the K content reduced the disease index (Sharma and Kolte, 1994). In rice, K application reduced the incidence of brown leaf spot (*Helminthosporum oryzae*) (Perrenoud, 1990).

In plants, K increases the production of disease inhibitory compounds, such as phenols, phytoalexins and auxins around infection sites of resistant plants. When K levels are below optimum, inorganic N accumulates and phenols, that have fungicidal properties, are rapidly broken down (Kiraly, 1976). Applied K decreased the severity of black spot disease in oilseed rape caused by *Alternaria brassicae (Sacc.) Berk* due to the increased production of total phenolics at all stages of plant growth. The phenolics inhibited conidial germination and decreased sporulation of *A. brassicae* (Sharma and Kolte, 1994).

The nutritional balance is frequently as important as the level of a single nutrient. This is perhaps one of the causes why K application in some cases can aggravate plant diseases (Table 3.7). The Ca and K balance determines resistance to gall diseases through their effect on cell growth and division. Increased susceptibility of potato to *Streptomyces* scab induced by high levels of K is probably related to drastically altered periderm cells and enhanced cell division (Huber and Arny, 1985), whereas the increased severity of brown rot gummosis (*Phytophthora parasitica*) of citrus trees induced by high K may be related to effects of the altered K/Ca ratio on the differential permeability of cell membrane (Chapman, 1965, cited by Huber and Arny, 1985). The correlation coefficients between ear leaf nutrient contents and smut disease index in corn showed variable significant effects between N sources, but attention was drawn to the N:(K+Ca+Mg) ratio in plant tissue for the better interpretation of the incidence of smut disease (Kostandi and Soliman, 1997).

3.8.1.2. Stresses

3.8.1.2.1. Lodging

Plant lodging is due to insufficient mechanical strength, to diseases or pests or to combination of these factors; and is strongly influenced by K nutrition (Quintanilla Rejado, 1978). Increases in the thickness of sclerenchymatic tissue layers by improved K nutrition are reported for wheat, rice and corn (Beringer and Nothdurft, 1985). Potassium speeds up lignification of the schlerenchyma cells and increases cell wall thickness, confering mechanical strength and thus resistance to lodging (Quintanilla Rejado, 1978; von Uexküll, 1993).

Large cereal yields require large application of N which the plant must tolerate without lodging. Nitrogen fertilization leads to much vegetative growth, and if K is not applied together with N, plants may lodge, especially certain varieties. In rice, K increases the thickness of the culm walls at the lower part of the stem, increasing the breaking strength of the culm and thus the resistance to lodging, especially when much N is applied (von Uexküll, 1993). Potassium application increased rape plant’s resistance to lodging, and decreased seed black spot disease infection (Sharma and Kolte, 1994).

Weak corn stalks are especially abundant with high rates of N and insufficient levels of K. Maintaining a sufficient K supply is necessary to prevent corn lodging with large plant populations (Welch and Flannery, 1985). Field trials in corn testing four levels of N, P and K showed that N and P had little or no effect on stalk quality characteristics, while K reduced the proportion of senescent stems and stem lodging, and increased the crushing strength and rind thickness (Arnold *et al.*, 1974). Results from 19 experiments in China show that K fertilization not only resulted in an increase in grain yield, but also reduced plant lodging, from 85% without K to 15% with 100 kg K ha^{-1} (Corazzina *et al.*, 1991). Potassium deficiency in corn reduces root development, especially of adventitious roots, which in turn, increases the risk of lodging (Quintanilla Rejado, 1978).

3.8.1.2.2. Frosting and chilling

Plants receiving an inadequate K supply are often more susceptible to frost damage (Marschner, 1995). Improved frost hardiness is attributed to a number of physiological and morphological factors like: healthy, deep roots, large xylem vessels, high content of sugars and reserve carbohydrates, reduced transpiration and water loss (Kemmler and Krauss, 1989). Potassium acts positively on most of these factors thus decreasing winter injury.

An adequate level of K in the plant can increase the osmotic potential in cell vacuoles, and thus increase the plant's chilling tolerance. It is recommended to keep high K concentrations in the soil and in the plant in order to increase the soluble carbohydrate content that may reduce the damage to plant tissues due to cold stress (Kafkafi, 1990).

The effect of different sources and levels of K on chilling tolerance was reported for seedlings of tomato, pepper and eggplant (Hakerlerker *et al*., 1997). Improved frost resistance due to K is also reported for potato, artichoke, strawberry, grapes, clover and lucerne (Beringer and Trolldenier, 1978).

Grewal and Singh (1980) found for potatoes an inverse relationship between the K content in the leaves and the percentage of foliage damage by frost in 14 field experiments conducted in India. Increasing K application, increased tuber yield and the K content of the leaves which, in turn, reduced frost damage. Another experiment in India showed that 167 kg K ha^{-1} reduced frost damage from 38% to 7% (Perrenoud, 1983). In India, KCl has established its superiority over K_2SO_4 in developing frost resistance in potato (Grewal *et al*., 1991). Therefore, in the north-western plains of India where frost is a problem, the application of KCl is recommended.

The importance of an adequate supply of K on winter hardiness of cereals has been well documented (Beringer and Trolldenier, 1978; Kemmler, 1983). In experiments done in the former Soviet Union, losses due to winter kill were lowest in plots that received a complete NPK treatment in autumn, followed by the plots with a KCl treatment (Kemmler, 1983). Khorshid and Seiji (1993) found that increasing the K application up to 350 kg K ha^{-1} increased the growth and winter hardiness of ryegrass.

3.8.1.2.3. Drought

It is well documented that plants adequately supplied with K can utilize soil moisture more efficiently than K deficient plants (Tanguilig *et al*., 1988; Li *et al*., 1993; Abd El-Hadi *et al*., 1997). Wilting of plants is a symptom suggesting possible K deficiency (Beringer and Trolldenier, 1978). The positive effects of K on drought tolerance are both through the enhanced water uptake by the roots and through the reduction of transpirational water loss (Beringer and Trolldenier, 1978).

Li *et al.* (1993) found that applying K to soybeans increased drought resistance through the increased development of vascular bundles in soybean roots, stems and leaves, and thus an increased ability to take up water and nutrients. Also K increased the bound water in cells and significantly increased yield under drought conditions.

Lösch *et al.* (1992) noted that water use efficiency by barley was improved up to 12% because stomatal size and density in the flag leaf differed between low (50 kg K ha^{-1}) and high K plants (200 kg K ha^{-1}). Thus leaf conductance, calculated from stomatal pore dimensions, was reduced when plants were supplied with 200 kg K ha^{-1}. Therefore, the beneficial effect of K on water use efficiency may stem from a better control of transpirational water loss as a result of modified stomatal sizes and densities (Lösch *et al.*, 1992).

Potassium application could lessen detrimental effects of drought and soil compaction on root growth and yield of upland rice (Tanguilig *et al.*, 1988). These authors found that 75 kg K ha^{-1} increased rice root mass density both in well-watered and stressed treatments. When K was applied, soil compaction did not decrease grain yield even with a low water supply.

Potassium application reduced significantly the decline in the photosynthesis rate of wheat leaves caused by drought stress (Gupta *et al.*, 1989). The protective role of K in plants suffering from drought stress has been attributed to the maintenance of a high pH in stroma and against the photo-oxidative damage to chloroplasts (Cakmak, 1997).

3.8.2. Chloride and diseases

The effects of soil Cl and plant nutrition on plant diseases have been the subject of a number of investigations over the past two decades. In studies of the influence of K on disease reduction (Huber and Arny, 1985), KCl was tested and the observed effects were ascribed to K, while the role of Cl was not considered. Chloride has been shown to aid in the suppression of diseases such as stalk rot of corn (*Diplodia maydis; Gibberella zeae*) (Younts and Musgrave, 1958), yellow rust (*Fusarium* spp.) in winter wheat (Russell, 1978), take-all root rot (*Gaeumannnomyces graminis* var. *tritici*) in wheat (Christensen *et al.*, 1981; Taylor *et al.*, 1981) and root and crown rot (*Rhizoctonia solani*) in sugar beet (Elmer, 1997).

Potassium fertilization reduced leaf rust (*Puccinia triticina*) severity and improved wheat yield by increasing grain weight, but this response was attributed partially to the Cl in the KCl fertilizer (Sweeney *et al.*, 2000). Christensen *et al.* (1981) showed that the Cl anion is responsible for the suppression of take-all root rot (*Gaeumannimyces graminis*) in wheat, provided there is sufficient K for optimum wheat nutrition. The lower chemical potential of water in roots supplied with Cl probably reduced root colonization by the pathogen. (Christensen *et al*., 1981). Chloride applied at 76 kg Cl ha^{-1} significantly increased grain yield by an average of 0.5 t ha^{-1} by reducing stress from take-all root rot (Scheyer *et al*., 1987).

Experiments comparing the effect of KCl vs. K_2SO_4 showed that yield loss due to take-all was higher with K_2SO_4 than with KCl (Trolldenier, 1985), and that KCl was more effective than K_2SO_4 in decreasing powdery mildew (*Erysiphe graminis*) development in wheat (Grybauskas *et al*., 1988). Common root rot (*Cochliobulus sativus*) in barley was significantly reduced by fertilization with KCl, but not with K_2SO_4 (Shefelbine, 1986).

The Cl suppression of root and crown rot (*Rhizoctonia solanis*) in sugar beets was independent of the Cl source. KCl, $CaCl_2$, $MgCl_2$ and NaCl did not differ in their ability to suppress the disease (Elmer, 1997). Both KCl and NH_4Cl equally reduced common root rot severity in barley (Shefelbine, 1986). In asparagus, both NaCl and KCl amelioriated Fusarium crown and root rot (*Fusarium oxysporum*), but NaCl was superior (Elmer, 1992).

Heckman (1998) confirmed the specific effect of Cl in controlling the incidence of corn stalk rot by comparing equal amounts of K supplied as K_2SO_4 or KCl. The Cl concentration in the ear leaf was increased more than four-fold by KCl and the incidence of stalk rot was reduced by more than half. Retention of moisture in the maturing plants and a delayed senescence due to enhanced Cl nutrition may explain the suppression of stalk rot.

Chloride in macronutrient fertilizers was found to partially control a number of plant diseases in different crop species (Table 3.8).

Whether these responses involve a direct effect of Cl on the plant pathogen or increased host tolerance has not always been clear. The effect of Cl appears to be distinct from that of its accompanying cation. Huber and Arny (1985) explained the early reported effects of Cl on stalk rot in terms of a competitive effect of Cl on NO_3 absorption (see Chapter 3.4.5), and the resulting influence on rhizosphere pH. Fertilization with KCl reduced common root rot in barley, and this effect was closely related to decreased NO_3 concentrations and increased Cl concentrations in the plant tissue (Goos *et al*., 1987). An important effect of Cl, when added to the soil in sufficient quantity, is the temporary suppression of nitrification (see Chapter 2.3). Huber and Wilhelm (1988) argue that inhibition of nitrification suppresses take-all and other diseases via a decrease in rhizosphere pH as a result of increased uptake of ammonium-N and decreased uptake of nitrate-N. This in turn increases the availability and uptake of Mn, which is implicated in disease suppression (Elmer, 1995). Ammonium may also affect host physiology in other ways, leading to increase the resistance to diseases. Christensen *et al*. (1986) provided clear evidence on the change in the ratio of soil NH_4 to NO_3 induced by Cl, and linked it to the suppression of take-all.

Table 3.8. Crops and associated diseases suppressed by chloride.

Crop	Diseases		Source
	Common name	Scientific name	
Asparagus	Crown and root rot	*Fusarium oxysporum*	Elmer, 1992
Barley	Common root rot	*Cochliobulus sativus*	Shefelbine, 1986 Goos *et al*., 1987
Celery	Fusarium yellows	*Fusarium oxysporum*	Schneider, 1985
Coconut	Gray leaf spot	*Pestalozzia palmarum*	Fixen, 1993
Corn	Stalk rot	*Diplodia maydis* *Gibberella zeae*	Fixen, 1993
Pearl millet	Downy mildew	*Sclerospora graminicola*	Fixen, 1993
Rice	Stem rot Sheath blight	*Helminthosporium sigmoideum* *Rhizoctonia solanis*	Fixen, 1993 Fixen, 1993
Sugar beet	Root and crown rot	*Rhizoctonia solanis*	Elmer, 1997
Wheat	Common root rot Glum blotch Leaf rust Stripe rust Powdery mildew Take-all rot Tanspot	*Helminthosporium sativum* *Septoria nodorum* *Puccinia recondita* *Puccinia striiformis* *Erysiphe graminis* *Gaeumannimyces graminis* *Pyrenophora tritici-repentis*	Fixen, 1993 Fixen, 1993 Fixen, 1993 Scheyer *et al*., 1987 Grybauskas *et al*., 1988 Scheyer *et al*., 1987 Fixen, 1993

An intriguing possibility is the direct Cl-mediated release of Mn from soils (Krishnamurti and Huang, 1988). Microbial activity could trigger a process whereby Cl increased the reduction of MnO_2, and thus increased the available Mn following application of Cl salts (Norvell, 1988). Chloride application increased the population of Mn-reducing bacteria, which increased Mn^{2+} concentration at the root surface at such a level that was toxic to Fusarium and suppressed root rot disease in asparagus (Elmer, 1995).

Potassium chloride applied as a foliar spray in wheat significantly reduced the percentage leaf area affected by powdery mildew (*Erysiphe graminis*) (Cook *et al.*, 1995). The reduction in the disease was associated with increases in the leaf water potential. This explanation was suggested as a polyethylene glycol solution with an equivalent osmotic potential to KCl also exerted the same effect. The authors concluded that both the inhibition of germination and the reduction of the disease symptoms may be due to the physico-chemical properties of the KCl fertilizer rather than metabolic toxicity or nutritional effects on the host.

Environmental conditions such as temperature, humidity and light intensity strongly contribute to the occurrence and severity of diseases, and also affect the uptake and physiological functions of the major nutrients. Thier *et al.* (1986) concluded that Cl fertilization of wheat grown under their experimental conditions did not offer any measurable protection against powdery mildew. Therefore, the local climate conditions during the growing season influence the relationship between the K and Cl nutritional status of crops.

3.9. Plant tissue analysis of potassium and chloride

3.9.1. Diagnosis of plant potassium nutrition

Leaf analysis has been widely used in an attempt to define the nutritional status of plants for fertilizer recommendations (Jones *et al.*, 1991; Reuter and Robinson, 1986). The concentration of tissue K is usually defined as low (deficient), adequate (sufficient), or high (excessive) concentrations for a particular plant organ (Table 3.9), sometimes at an identifiable plant developmental stage, but the definition of "low" and "high" concentration varies between plants (Table 3.4).

Potassium uptake usually precedes dry matter production (Fageria *et al.*, 1991). Leaf K concentration varies with time during growth (Kafkafi *et al.*, 1978). Values of critical leaf K content for field crops vary between 12 g kg^{-1} and 20 g kg^{-1} (Table 3.4) at about shooting or flowering stage (Fageria *et al.*, 1991). The critical value depends on crop, variety, growth stage, sampled vegetative part and climate. A significant positive relation between K concentration or K accumulation of leaves and stems at flowering and final grain or fruit yield was presented by Kafkafi and Xu (1999). High concentrations of K may be necessary to achieve high yields and the desired large fruit size to meet market demand.

Potassium is required for the proper functioning of a large number of enzyme systems at a concentration of about 50 to 100 mM in the cytoplasm (Barraclough and Leigh, 1993a; Marschner, 1995), however, the concentration is larger in K sufficient plants, of the order of 200-300 mM (Table 3.9).

Table 3.9. Potassium concentration in *Valencia* orange leaves.

		Level		
Parameters	Unit	Low	Adequate	High
K concentration in DW	g K kg^{-1} DW	8.3	11.2	18.1
DW content	g DW kg^{-1} FW	413	401	382
Water content	g H_2O kg^{-1} FW	587	599	618
K concentration in FW	g K kg^{-1} DW	3.4	4.5	6.9
K concentration in leaf solution	mM K	149	192	286
K concentration in leaf solution	g K m^{-3}	5826	7507	11183

Recalculated from Smith *et al*. (1953).

Critical plant K concentrations for growth are related to different functions of K in plants. For example, critical K concentrations in ryegrass were 126 mM (19 g kg^{-1} in DM) in plants grown on low Na soils and 82 mM (13 g kg^{-1} in DM) on high Na soils, respectively, for the biophysical function of maintaining leaf sap osmolality. However, the critical K concentration in ryegrass was 46 mM (8 g kg^{-1} in DM) for the purely biochemical functions of activating numerous enzymes (Barraclough and Leigh, 1993b). Bell *et al.* (1997b) inferred the functional K concentration to specific plant functions. Increase in putrescine levels or decline of pyruvate kinase activity are observed when K deficiency exists. These changing activities may provide a more accurate and consistent value for the diagnosis of K deficiency, but they are much more expensive and cannot be used for routine laboratory analysis.

The traditional approach to plant analysis expresses nutrient concentration on a dry matter basis. Concentrations and critical concentrations expressed in that way change with the age and type of tissue and with other growth factors such as the supply of other nutrients (Jones *et al.*, 1991). This greatly reduces the utility of plant testing for diagnostic purposes. In contrast, expressing nutrient concentration on a tissue water basis has several advantages (Leigh, 1989). It is more physiologically relevant especially for K because of its importance in plant water relations. Potassium concentrations in tissue water (K_{H_2O}) change less with plant development than do K concentration in dry matter (K_{DM}). In hydroponically grown barley well supplied with K, the K_{H_2O} was constant at about 200 mM in all leaves throughout the plant growth (Barraclough and Leigh, 1993b). This was also the case for whole barley tops in the field during vegetative growth (Leigh and Johnston, 1983). More work is needed on the effects of water supply on K_{H_2O} and critical K_{H_2O} concentrations in crops. Special attention must be paid to leaf sampling in the field to avoid water loss between sampling and weighing in the laboratory.

Hochmuth (1994) presented guidelines of plant petiole sap quick-testing of K for vegetable crops and suggested critical values. Reasonable standardization of sampling including crop developing stage, leaf age, leaf part, weather condition, time of day and calibration scale, is necessary. A standard time in the day is needed to establish sampling procedures as the petiole salt content varies very quickly during the day (Saranga *et al.*, 1998).

It is generally recommended to collect fleshy petioles of most recently matured leaves which have reached maximum size. The leaf blades should be stripped from the petioles and petioles placed in a plastic bag on ice or in a cooler. Petioles may be stored at room temperature in a plastic bag for up to 2 h. Only petioles, not sap, should be stored. Fresh, whole (unchopped) petioles can be stored on ice for up to 8 h or frozen overnight without appreciable changes in sap K concentration.

The critical K concentration in the sap of fresh petioles varies from 1500-2000 g m^{-3} for strawberry at its late growing stage, up to 4500-5000 g m^{-3} at the early to middle growing stages of some common vegetables, such as eggplant, potato, glasshouse tomato and watermelon (Hochmuth, 1994).

3.9.2. Analytical determination of plant potassium

Nearly all the K in plant is in the form of ionic K^+ and can be extracted from ground dry plant samples by diluted acids or salts, such as 1 M HCl, HNO_3, NH_4OAc, and even by hot water (Chapman and Pratt, 1961). In many cases the K analysis of plant is performed together with other nutrients, particularly N and P.

There are two types of methods of plant tissue decomposition for the analysis of total amount of mineral nutrients: dry ashing in a muffle furnace often at 500-550°C and wet digestion with strong oxidative acids. Usually dilute acids, such as 1:1 HCl or HNO_3, are used to acidify the dry ash and dissolve the elements to solution. Common reagents used to digest plant tissue include the acids: H_2SO_4-H_2O_2, H_2SO_4-HNO_3-$HClO_4$, HNO_3-$HClO_4$, etc. (Benton Jones *et al.*, 1991).

Potassium in the extracted solution is often determined by FES method as described in section 2.4.1.2.

3.9.3. Diagnosis of plant chloride nutrition

A number of studies have been conducted to determine the need for Cl for several crops (Fixen, 1993). The strong correlation between the Cl level in lettuce leaves and soil Cl content is used to monitor the environmental Cl level (Wei *et al.*, 1989). Leaf chloride levels of Spanish moss (*Tillandsia usneoides* L.) reflect the atmospheric Cl levels on the coast of Texas (McWilliams and Sealy, 1987).

Plant Cl concentration varies greatly with plant age and plant part. The concentration in spring wheat generally increased with time to about 4.5 g kg^{-1} and 13 g kg^{-1} when grown with 255 kg Cl ha^{-1} and without Cl respectively, until 1 or 2 weeks prior to heading, and then declined to less than 1 and 2.5 g kg^{-1} at maturity, respectively (Fixen, 1993). It is apparent from these data that plant Cl is more dynamic over time in high Cl environments than where Cl supply is limited. Chloride concentration can also vary markedly among plant parts. Hence, interpretation of results from plant analyses, as for all nutrients, requires that careful attention is paid to the growth stage and plant part sampled.

There are several other factors influencing plant Cl concentration, such as differences between cultivars and interactions between Cl and some other elements as discussed earlier. The Cl concentration in plants is a useful predictor of the potential for response to Cl fertilization. Engel *et al.* (1994) made a comprehensive summary of the relationship between crop Cl and the yield response of wheat and barley to Cl as shown in Fig. 3.17. It is possible to distinguish three different levels of Cl nutrition: low, <1.2 g kg^{-1}, significant response expected in 78% of cases; transition, 1.2-4.0 g kg^{-1}, response expected in approximately 50% of cases; and adequate, >4.0 g kg^{-1}, few significant responses to Cl likely.

3.9.4. Analytical determination of plant chloride

Similar to plant K, plant Cl is always ionic and can be simply extracted by a weak acid, or even hot water. The methods used for Cl determination in soil extracts (see above section 2.4.2.2) are also often used for plant Cl. In order to minimize interference with either electrode methods, Cl is determined in either a 0.5 M HNO_3 extract of the plant tissue, or the determination is made after the tissue is dry ashed in the presence of access calcium oxide to prevent Cl loss by volatilization during ashing and the ash is solubilized in dilute HNO_3 (Chapman and Pratt, 1961).

Williams (1979) described the classic procedures of Cl determination in plant tissue. The Cl-specific, ion-electrode procedures (LaCroix *et al*., 1970; Krieg and Sung, 1977), or a solid state Cl electrode (Islam *et al*., 1983), are used in place of the gravimetric and volumetric methods. The analysis of Cl using a potentiometric titration procedure is the same for the determination of Cl in soil extracts, except that the concentration of the titrant is generally increased (LaCroix *et al*., 1970). Ion chromatography is described by Kalbasi and Tabatabai (1985) as well as by Grunau and Swiader (1986) for the determination of Cl in plant tissue.

3.10. A glance into the future: biotechnology, genetic engineering and potassium

The term biotechnology relates to accelerated breeding using DNA markers and transgenes that modify and improve the current crop production systems (Lightfoot, 1999). The results of this biotechnological manipulation are GM (genetically modified) crops:

- Transgenic crops developed for specific traits, with inserted genes that confer resistance to insects and viruses or tolerate specific herbicides. Other specific improved traits which are being sought include crops with increased constituents such as oil, starch, sucrose or gluten; for example, high oleic acid soybeans, or high lysine soybean and corn.
- Nutraceutical and functional foods, strains that yield valuable proteins, enzymes or other substances, which provide medical or health benefits, including for example plant based vaccines to prevent diarrhea and other diseases. GM fruit and grain crops may also become the vehicle for boosting intake of carotenoids, antioxidants, vitamin E, folates, etc. which have been linked to the prevention of cancer, coronary disease and degenerative nerve diseases.

The adoption of GM crops by U.S. farmers is growing very fast: GM corn accounted for 35% of the US acreage in 1999, up from 28% in 1998. In 1999, GM soybeans were seeded in 40 million acres, or 55%. GM cotton will total more than half of acreage. GM potatoes are also grown and GM sugar beet are to make their debut. These GM products offer farmers tools to increase yields while lowering costs with little change in agronomic practices. However, the in-field use of GM crops is a highly controversial issue involving consumer welfare, agricultural economics, environmental and biodiversity impacts, international trade, and has strong opposition in Europe.

Current transgenic crop developments are not focused on reducing fertilizer inputs, but on reducing pesticide inputs. Some examples are the 'Roundup ready soybeans' which have the gene conferring resistance to Roundup herbicide; 'Poast-protected corn' which has the gene that gives corn tolerance to Poast herbicide, and 'Bt corn' that has a gene derived from *Bacillus thuringiensis* that produces a toxin which kills insects.

Transgenic lines for high-yielding crops *per se* are not yet being developed, because a large number of genes are thought to be responsible for yield, and these genes have not yet been identified and isolated. If gene manipulation will increase yield directly, this may result in the removal of larger amounts of nutrients from the soil and perhaps increased fertilizer needs, if current levels of inputs are not used more efficiently.

Nutrient management may be indirectly affected by GM transgenic crops if they eliminate one or more yield limiting factors. With better weed and pest control, crops are more likely to reach their yield potential and then could be more responsive to fertilizers. So far, studies on the nutrient use efficiency of transgenic crops are scarce. If GM crops use nutrients in the soil more effectively, theoretically, this could decrease the need for fertilizer. The specific requirements for fertilizer of GM crops have been scarcely studied, and the impact of biotechnology on plant nutrition and fertilizer use is yet to be determined.

There are some examples of GM crops in which N and P biochemistry in the plant has been altered. These include the 'GDH corn', in which a gene that produces the enzyme NADP-dependent glutamate dehydrogenase has been introduced from soil bacteria. In the plant, this enzyme causes increased N assimilation and about a 10% increase in yield. Another example is a transgenic *Arabidopsis* plant with modified expression of high-affinity nitrate transporters. This may be a future transgenic approach to improve N use efficiency in economical important crops. Regarding P, 'low-phytate corn' has been obtained and yields well with smaller P inputs, accumulates P in vegetative tissues, contains less P in grains but in a form suitable for non-ruminant digestion (Lightfoot, 1999).

So far, there have been no direct or specific developments for commercially engineering GM crops involving K. However, as far as balanced crop nutrition is involved, modifications in N and P uptake and efficiency will affect K inputs.

A future approach involving GM and K may use the HKT1 gene (high-affinity K transporter), which is an important component of the high affinity K uptake system in roots and has been isolated from wheat (Schachtman and Schroeder, 1994). Transgenic wheat plants containing this gene were produced in the lab. Potassium uptake by the plant was studied under K deficient conditions (Laurie *et al.*, 1998). Transgenic plants with a modified activity of the K transporter may have an altered K metabolism which could lead to higher yields.

Another interesting challenge is the achievement of salt tolerant plants. There is a substantial and increasing knowledge of the molecular biology and molecular genetics that affect cell-based tolerance to salinity (Yeo, 1998).

Some early results show that mutation of HKT1 in yeast strains carrying the gene results in improved salt tolerance and an increase in internal K/Na ratios indicating improved K selectivity under salt conditions (Rubio *et al*., 1995). Yet the whole-plant response to salinity involves many regulatory processes and multiple gene transfer, thus the practical technology for developing salt tolerant crops through genetic manipulation is still unavailable (Yeo, 1998). A possible impact of transgenic salt tolerant crops would be the ability to use KCl under saline soil conditions.

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