Potassium for Sustainable Agriculture

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K.R. Hakeem et al. (eds.), *Soil Science: Agricultural and Environmental Prospectives*, DOI 10.1007/978-3-319-34451-5_7

Abstract Potassium (K) is the third most important plant nutrient required in higher amounts by plants. It plays role in charge balancing, osmotic adjustments and enzyme activation in plant cells. It is highly mobile in the plant because it is not the structural part of plant tissue, but is present in ionic form in the plants. Although about 2.3 % of the earth's crust consist of K, but most of its parts bound with clay minerals and is not available to plants. Release of K from micaceous soils not only provides an essential plant element, but also converts mica into illite and vermiculite with more sites for K absorption. Therefore, K fertilization in such soils may cause K fixation and most of K applied become unavailable or slowly available to plants. Potassium is also named as a quality element because it improves the agricultural-product quality. Potassium also develops resistance against different environmental stresses and has ability to mitigate biotic and abiotic stresses developing immunity in the plants. In human and animal nutrition, K has significant role and its deficiency in humans can cause cardiovascular and nervous diseases. The ultimate source of K in human nutrition is the soil which provides K to plants and is then used by humans and animals. Potassium fertilizers need to be applied to the soils to replenish the exchangeable K and non-exchangeable K for sustainable soil fertility, otherwise severe deficiency of K may happen which will be even more difficult to cure. As K has strong interaction with clay minerals, therefore it is intensely recommended to apply K fertilizers based on soil mineralogy and K dynamics in the soil. Although K in soil is evaluated by three standard methods, including visual observations, soil analysis and plant tissue analysis, however, for sustainable agriculture site-specific K recommendations based on soil mineralogy are direly needed to have a better crop response and economical agricultural productions.

Keywords Sustainable agriculture • Plant nutrients • Potassium • Crop yield • Fertilizers

1 Introduction

Potassium (K) plays a key role as inorganic osmoticum and its impact on leaf movement, stomatal regulation, axial growth and tropisms are well recognized (Marschner 1995; Shabala 2003; Ahmad et al. 2013). Among the mineral nutrients, K is the 2nd most abundant element in plants and contributes 2–10 % of plant dry weight (Tisdale et al. 1993). Potassium is a counter ion for the charge balance and ion transport across the plasma and intra-organelle membranes (Dreyer and Uozumi 2011; Shabala 2003). Potassium also controls the process of photo assimilates loading into the phloem (Ache et al. 2001; Gajdanowicz et al. 2011). There are over 70 enzymes, the activities of which were shown to be sensitive to K (Marschner 1995).

Over 250 years, K fertilizers were derived from wood ashes and livestock manure, traditionally. However, since 2000, global potash demand has grown by 40 %, with over 50 million tons of potash produced in 2012. Globally, above ground parts of annual crops contain 60 million tons of K.

1.1 Potassium Dynamics in Soil

Most of the soils are abundant in K because 2.3 % of the earth's crust is occupied with the K-minerals; however, this part of the K is mostly bound to clay minerals and is not available for plant growth. Soil solution concentration represents the most available form of K to plants. Potassium released from exchangeable as well as non-exchangeable to solution form improves soil solution concentration. Capacity of soil represents the total K amount in soil which is readily available to plants, while soil intensity represents concentration of K in soil solution which is readily available for plants. Mica minerals contain 6–9 % K while alkali feldspars contain 3.5–12 % K and both represent major natural reserves for plant available K after weathering. Potassium uptake by plants reduces its concentration in rhizosphere in the roots vicinity which ultimately stimulates the K-release from the minerals (Kuchenbuch and Jungk 1984). That release of K not only provides nutrition to plants but also change micas to illite and then to vermiculite as explained in Fig. 1 (Havlin et al. 1999; Wakeel et al. 2013). Application of K fertilizers to such soils may lead to fixation of K to those soil minerals, making them slowly available or unavailable for plants (Scott and Smith 1987). Nevertheless, fixed form of K is again released and is available to plants when K concentration of K in soil solution is lowered (Cox et al. 1999). Smectites are also K-fixing clay minerals with layer charge of 0.2–0.6 per half unit-cell, CEC 0.8–1.2 mol (+) kg^{-1} soil and layer thickness 1.0–2.0 nm (Bohn et al. 2001).

Therefore, in K fixing soils, sometimes, higher recommended levels of K fertilizer do not show improvements in plant growth; but a much higher fertilizer dose is required to get a response (Doll and Lucas 1973; Mengel and Kirkby 2001). Such

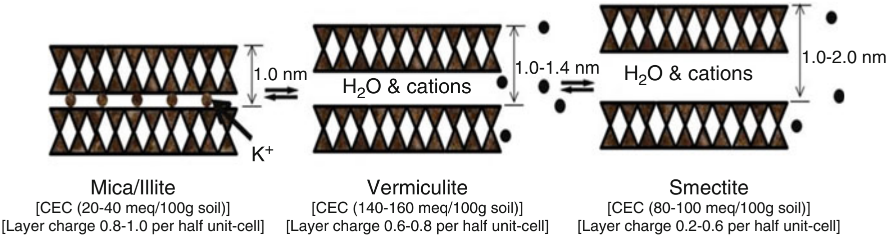

Fig. 1 Release of K during mineral weathering and its fixation by clay minerals. *CEC* cation exchange capacity (Havlin et al. 1999)

soils are rich with vermiculite and illite clay minerals with high CEC and fixed most part of applied K which is unavailable to plants.

1.2 Potassium Dynamics in Plants

Potassium is an essential plant element and higher plant required in large amounts. It is highly mobile in the plant, as it is not the structural part of plant and is present in ionic form in plant tissue. In the plant cell, cytosol maintains highest K concentration in the range of 130–150 mM (Leigh 2001), while the K range is 20–100 mM in the vacuole, which also indicate supply of K to the plants (Fernando et al. 1992). Potassium is performing three main functions *viz.* osmoregulation, enzyme activation and charge balance in the plants (Schubert 2006).

Potassium ions assumed to bind to the enzyme surfaces to activate them by changing their conformations. These enzymes basically involved in many vital functions of plant cell, including ribosomal polypeptide synthesis (Jones and Pollard 1983). It has been reported that K is centered with six oxygen atoms in the corner in an octahedron of enzyme dialkyl-glycine decarboxylase (Miller 1993; Fig. 2).

The electrochemical difference between the outer medium and cytosol is basically a main process for ion transport. Plant membranes are relatively permeable for K due to the presence of K selective channels, developing ease for K to play its role in charge balancing to maintain various activities in the cells. When an electrochemical potential is lower in the cytosol than outer medium, K ion move into the cell to maintain electrical balance. K ion import improves the electrochemical potential and attains the final equilibrium (Mengel and Kirkby 2001). The cytosolic

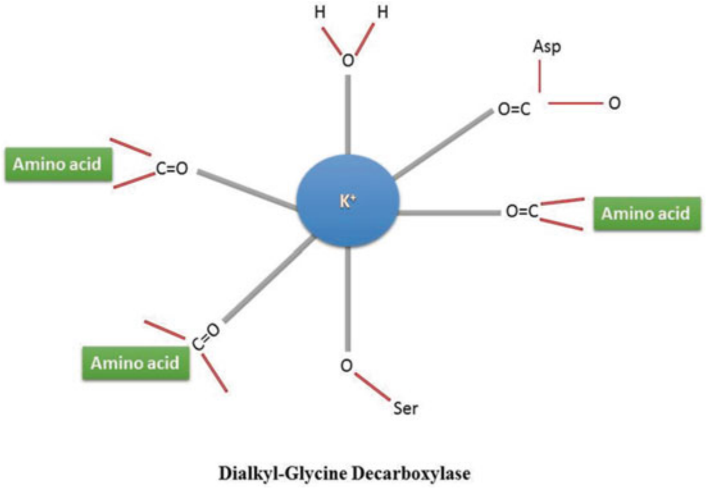

Fig. 2 Potassium complexed by organic molecules of which the oxygen atoms are oriented to positive charge of K^+ (Adapted from Miller 1993)

negative charge is sustained by the activity of proton pumps. Released H^+ ions by plasmalemma H^+ pumps from the cytosol into the apoplast sustain the negative charge in the cytosol maintaining it in the range of 120–200 mV.

Similarly, K enters into the stroma for charge balance using the charge gradient produced by the H^+ pumped out of the stroma (Berkowitz and Peters 1993).

Potassium may accumulate in the vacuoles at high concentration (Hsiao and Lauchli 1986), where K also functions as an osmoticum and maintain turgor potential in the guard cell by water uptake from the soil (Moran et al. 1988) and in the phloem (Mengel and Haeder 1977; Smith and Milburn 1980).

1.3 Potassium vs. Other Cations

The main cations essential for plant growth include ammonium, calcium, magnesium, and K. Among others, sodium (Na) and aluminum (Al) have significant impact on crop growth by influencing soil pH. Plants have cation transport systems at plasma membrane which are cation specific as well as non-specific. In soil a certain ratio between K and other cations such as Ca, Mg, and Zn etc. should be maintained for better nutrient uptake. Application of too much Ca and Mg can cause a K deficiency due to the competition between Ca, Mg and K. A realistic ratio between K and Ca or Mg is 2 or above for optimum K uptake by plants. However, excessive application of K can also decrease the uptake of Ca and Mg, as well as micronutrients such as Zn. Therefore, K/Ca or K/Mg ratio should be less than 10 for optimum Ca and Mg uptake. It is particularly important to take into account of this interaction when using hard water with a high calcium and magnesium concentration.

Potassium and ammonium (NH_4^+) both have the same size and valence properties, consequently always compete with each other for non-exchangeable and exchangeable soil-particles sites. Nitrogen fertilizer may affect the availability of K^+ in long as well as short term usage. In case of long term activities, NH_4^+ fertilization depleted non-exchangeable and exchangeable K^+ from the soil, while in short term activity, soil solution K^+ concentration may increase with increase in NH_4^+ fertilization. K transport through plant membranes is mainly affected by NH_4^+ because of direct competition between NH_4^+ and K^+ for different transporters (Zhang et al. 2010).

Numerous investigations have concluded that only K is the monovalent cation which is essential in all higher plants; however, Na may also promote the biomass production of some plant species without meeting the criteria of essentiality (Flowers et al. 1977). Elements having similar physicochemical properties may perform equally well in a metabolic process and it appears that K and Na may replace each other partially for few nonspecific osmotic or unspecific metabolically active functions. Various studies have revealed that plants may require K in lower amount particularly for cytoplasmic activities which cannot be replaced by any other cation, however, about 90 % of total K localized in vacuoles performing osmotic functions can be substituted by some other cations having similar physicochemical properties

(MacRobbie 1977; Leigh and Jones 1986). In some halophytic plant species, Na may stimulate the plant growth by cell expansion and replace K partially for osmotic functions (Nunes et al. 1983).

1.4 *Ionic Uptake and Homeostasis*

Water and nutrients move towards stele through root cells by two ways, (1) through apoplast and/or (2) via symplast (Fig. 3). Although, before being part of stele, casparian strip due to its hindrance may enhance ions to enter into the symplast. Then these translocated ions enter into epidermal or cortex cell through symplastic way, and loaded into the stele which made up of living cells of parenchyma and elements of dead trachea for further translocation to the shoot. Because dead elements have no cytoplasm continuity and through the crossing plasma membrane, ions must leave the symplast (Taiz and Zeiger 2006).

The Na influx distorted the plants ionic ratio through K transporters or pathways. This similarity of both monovalent K and Na ions make it tough for cells to discriminate between each other. Sodium enters into the plant cell through two pathways i.e. either through non-selective cation channels (NSCC; Amtmann and Sanders 1999) or through high-affinity K transporters HKT1 (Rus et al. 2001). NSCC also allows calcium to pass through. Transport of cations in maize to xylem may control through an outward-rectifying cation channels (ORCC) via root stellar cells (Roberts and Tester 1997). Although outward-rectifying cation channels (ORCC) are highly K selective channels, but also allows Na and Ca to move through in lesser extents (Cramer et al. 1994). Sodium also interferes with Ca uptake in

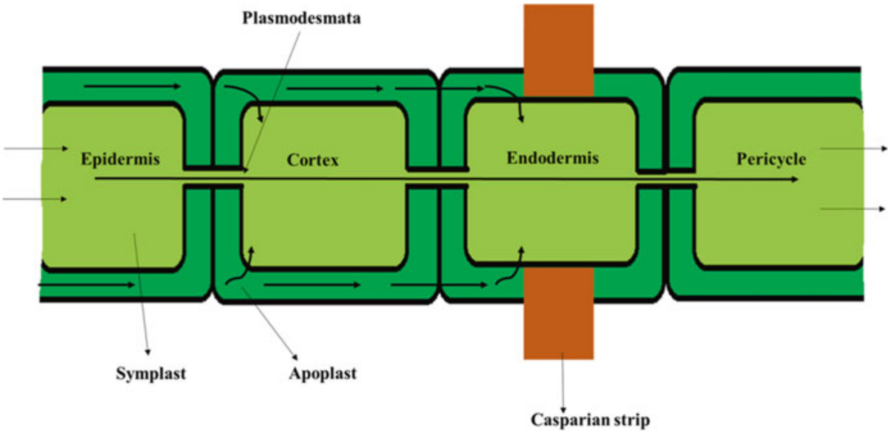

Fig. 3 Two pathways of nutrients movement within root cells to the stele

gramineous plants, and sugar beet plants have also shown Ca deficiency symptoms when Na was increased in the soil, even in a very small concentration (Abd-El-Motagally 2004; Wakeel et al. 2010).

2 Potassium in Agriculture

Potassium functions and requirements are specific for all crops. It maintains cell turgor by increased water content, movement of water and nutrients relationship through the plant and sugar transport to storage organs i.e. beet roots, grains, fruits, tubers etc. Potassium is also named as ‘quality element’ which ensures the quality agricultural produce. Here we review and discuss the role of K for crop yield enhancement, quality crop produce, resistance against environmental stresses and sustainability of agricultural lands.

2.1 Crop Yield Enhancement

Potassium fertilization affected plant density, which consist of leaf length, width, total number of leaves, stem diameter, plant height, dry leaf yield and yield attributes of tobacco affecting its leaf length, width, stem diameter, total number of leaves, plant height, and total biomass. Foliar and soil application of K together increased wheat grain yield (Arabi et al. 2002). Only a foliar application may not provide the amounts required for a macro nutrient such as K to show high effects. In K deficient soils, the increased grain yield may be attributed to a significant increase in the number of tillers, plant height, leaf area index, spike length, 1000 grain weight, and water use efficiency (Mesbah 2009). It was concluded that K application at different growth stages with different rates may improve growth and yield of wheat crop.

Potassium also promoted plant growth, development and biomass yield of maize (Davis et al. 1996). Balanced fertilization can improve the plant growth; however, most of the farmers use higher amounts of nitrogen and phosphorus with lower K fertilizers. Application of K increased 17 % rice yield, generally reported from different parts of the rice grown area (IPI 1986). Bhatti et al. (1981) determined that K fertilizer applied at the rate of 90 kg ha^{-1} for paddy rice proved economical dose for better crop growth. Recommended economical dose of K fertilizer at the rate of 60 kg ha^{-1} was also recommended for rice grown on different soil (Rehman et al. 1982; Krishnan 1977). Khattak and Bhatti (1986) studied the effect of K and phosphorus on wheat and maize yield and reported that phosphorus was applied during first season, which was sufficient for further 2–3 seasons but potash was sufficient for 4th and even 5th crop. Siddique et al. (1997) reported that a K fertilizer dose of 110 kg ha^{-1} was optimum for wheat yield. Potassium fertilization of 40 kg ha^{-1} can increase 21–35 % of paddy and wheat yield (Hussain and Yasin 2003). Foliar application of K fertilizer also increased different parameters of wheat crop, and increase straw- and grain yield as was observed with the application of 1 % or 5 % KCl solution (Abdi et al. 2002).

Most K uptake in wheat takes place as the shoot is undergoing its rapid phase of growth (Gregory et al. 1979). For cereals, more than 70 % of K remains in the straw. Data from a long-term fertilization experiment demonstrate that this value is not fixed, but depends on cereal species and fertilization level. The K concentration in straw was strongly increased by K fertilization in barley and in wheat (Fig. 3). In practical agriculture, straw and thus significant amounts of K may remain on the field or be removed as a source of biomass. How crop residues are handled is, therefore, very important when calculating the fertilizer requirements.

2.2 Product Quality

The crop quality is a versatile parameter and might combine complex parameters such as a certain metabolite concentration, nutritional value, taste, processing properties, appearance, shelf life and technological quality. Plant product quality is the main focus of the producer’s revenue, it serves as a major point for the price of the product in market and quality of the product is more important for consumers (Pettigrew 2008). All these quality parameters are controlled by genetic makeup and physiological impact; however, K also plays a special role in quality formation because of its involvement in protein synthesis and transport of Photo-assimilates from source to sink (Allen and David 2007). It is necessary to balance other nutrients with K for better product quality. Although, product quantity is the principal function driving the producer’s revenue stream, product quality is important for consumers and often serves as a criterion for the market price of the crop (Pettigrew 2008). This is most evident for highly processed products such as wine, but also for other crops (Zörb et al. 2014). Although, a huge world population is striving for only food without considering the quality, but at the same time consumers nowadays also require better quality produce, and are willing to pay even more for good quality food. Balanced nutrition with adequate supply of K fertilizers depicts beneficial effect on the harvested product quality and improves nutritional value such as protein content, vitamins and oil contents. Optimum supply of K in crops may lead to better taste, flavor and appearance, and food production without- or less disease and pests attack. Application of K ensures the quality and yield of cotton, tobacco, banana, potato and many food crops. For example, K nutrition substantially influences the concentration of reducing sugars in potato, which are critical precursors for acrylamide formation during frying. An inverse relationship of reducing sugar concentration and K supply has been observed in most cases (Marschner and Krauss 1980). Gerendas et al. (2007) clearly demonstrated that tubers grown with high N and low K fertilization accumulated most precursors for acrylamide formation during frying. As reviewed in Zörb et al. (2014), K plays an essential role for grapevine growth and yield as well as for wine quality (Mpelasoka et al. 2003). Grape berries function as a strong sink for K, especially during the onset of ripening and volume increase, thus their juice contains this ion as major cation. However, the too high K concentration decreases free organic acids, increases the overall pH, lowers the tartrate-to-malate ratio, increases the tartrate precipitation during winemaking and reduces the overall wine quality (Somers 1977). In cereals it increases grain size and improves starch quality. Potassium improves color and flavor in vegetables and increases sugar contents, vitamin C and size of fruits. In addition, it helps in the maintenance of quality of storage, transportation and prolongs the shelf life (e-ifc, 2007). For export to developed countries, quality production is very critical, because the quality parameters include nutritive as well as healthy products. Therefore, K has significance for healthy agricultural productions.

2.3 Potassium and Environmental Stresses

Environmental stresses are great contributors to yield reductions of different crops. Potassium develops the abilities in plants to resist against biotic and abiotic stresses like pathogens, insects, salinity, drought and other abiotic stresses. The role of K is very significant and clear to develop immunity in plants and is discussed briefly.

2.3.1 Biotic Stresses

Biotic stress is stress caused by living organisms such as bacteria, viruses, fungi and insects which damage the plant. Pathogen attack activates the superoxide-generating NADPH-oxidases (Bolwell and Wojtaszek 1997; Lamb and Dixon 1997); however, K nutrition has a significant impact on the plant to develop resistance against these pathogens and decrease the incidence of diseases (Prabhu et al. 2007). Adversely, K deficiency can cause defense signaling reduces the crop growth (Amtmann et al. 2008), therefore, K supply during early growth could strengthen the inherent defense potential of plants to pathogens. Potassium transport systems are considered to be very important for plant responses to viral infection and the virus-host recognition. In recent studies, significant changes in K fluxes have been observed in response to microbial inoculation and Ca^{2+} signaling seems to be less essential in recognition of the early stages of viral infection (Shabala et al. 2010). Such K fluxes are assumed to be performed by outward rectifying channels abundantly formed in the plasma membrane in response to viral infection. The physiological rationale behind may be the ejection of viral DNA into the host cells by reduced cell turgor pressure. Potassium fertilization decreases the disease and insect attack in plants. Perrenoud (1990) reviewed that use of K fertilizers reduces the insects and mite infestation by 63 % and increase the yield up to 36 %. Increased synthesis of high-molecular-weight compounds in K-sufficient plants and decreased production of low-molecular-weight compounds inhibit the insect attack (Marschner 2012). Higher K^+ concentrations also decrease the chance of insect infestation by developing stronger cell walls (Mengel 2001).

2.3.2 Abiotic Stresses

Potassium concentration may vary in different parts of plant-cell such as cytoplasm, vacuole etc. (Leigh and Jones 1984). K concentration in the cytoplasm is maintained and remain constant (Leigh 2001) but in vacuole its concentration substantially varies depending on the provision of K$^+$ to plants. Plant performance was better under cold stress, when K concentration was a luxury in consumption in plant (Bergmann and Bergmann 1985). Before stress initiation, K concentration was not a luxury in plants, but plant allows surviving with different strategies under sudden hidden abiotic stresses (Kafkafi 1990). When K supply was low in early vegetative growth of plants, its structure suffers completely and express frost damage and lodging to unhealthy plants as compared to healthy.

(a) *Drought stress*

Soil moisture availability in arid and semi-arid regions is a major limiting factor for crop production. The root elongation rate is crucial for uptake of nutrients and water which have usually low concentration in soil-solution and are adsorbed strongly to the soil (Kafkafi 1991). Drought and heat stress effects can be mitigated by increasing K concentration in soil (Kafkafi 1990; Cakmak 1994). Under low moisture condition, K fertilization increased growth and yield (Sharma et al. 1996; Yadav et al. 1999; Egilla et al. 2001). Drought stress affects the protein synthesis, enzyme activation, water relation and stomatal conductance in plants (Marschner 1995). Optimum K fertilization increased water potential and minimize leaf osmotic potential of *Vigna radiata* (Table 1) as compared to untreated plants (Nandwal et al. 1998), wheat (Pier and Berkowitz 1987; Sen-Gupta et al. 1989) and maize (Premachandra et al. 1991) grown under drought. Nitrogenase activity, dry matter and nodulation increased with a supply of incremental K at ¼ of field capacity moisture level in broad beans (Abd-Alla and Wahab 1995). Potassium plays a major role in osmotic adjustment and accumulated higher amount of solutes in soybean, tropical grasses and maize under drought condition (Ford and Wilson 1981; Itoh and Kumara 1987; Premachandra et al. 1991). Stomata control water plant water loss through transpiration stream. Under K-deficient condition, stomatal function disturbed and water losses cause injurious effects on the plant at damaging levels (Gething 1990).

Under water stress, stomata close and efficiency of carboxylase activity reduced in chloroplasts. This long time closure of stomata leads to photo-reduction of O_2

Table 1 Effect of K$^+$ on water and osmotic potentials and relative water content in *Vigna radiata* leaves under water stress condition

	Water potential ($^-$MPa)		Osmotic potent ($^-$MPa)		Relative water content	
K$^+$ application (mmol dm^{-3})	Control	Stress	Control	Stress	Control	Stress
0.65	0.55	0.84	1.34	1.55	80.9	72.3
3.20	0.47	0.78	1.30	1.76	84.2	74.7
4.50	0.50	0.79	1.22	1.73	86.1	76.9

into toxic species. Though, drought stress causes a more severe effect during the inadequate K supply (Humble and Raschke 1971). Water stressed plants require more K because K play protective role against stress induced photo-oxidative damage. The K in the protective role under drought stress is well documented (Pier and Berkowitz 1987; Sen-Gupta et al. 1989). Plants photosynthetic efficiency is drastically (Table 2) reduced due to dehydration of chloroplast under drought stress (Berkowitz and Kroll 1988).

(b)Salt stress

Salt-affected soils have a higher concentration of Na^+ as compared to Ca^{2+} and K^+ ions, which results in Na^+ passive accumulation in shoot and root (Bohra and Doerffling 1993). Higher Na levels, disturbed cell membrane integrity and K ions selectivity uptake displace Ca through root membranes (Cramer et al. 1985, 1987). K ion loading into xylem is generally regulated by uptake of K from external K solution (Engels and Marschner 1992). This specifically reduced K uptake under salinity stress interferes K movement towards the shoot resulting in lower K uptake in the shoot and increased K concentration in the root (Table 3). This inhibitory effect on K translocation within plant was reduced by K supply at higher concentration; yet in maize grown in nutrient solution was stronger with application of low K fertilization (Botella et al. 1997).

Similarly, application of K fertilizer increased K concentration in spinach tissues, reduced growth differences among plants grown in high and low salt concentration (Chow et al. 1990). The salt concentration induced shoot-growth inhibition

Table 2 Effect of water stress and K^+ supply on net photosynthesis rate in wheat leaves

	Photosynthesis (μmol CO_2 m^{-2} s^{-1})		
K^+ application (mM)	*Low water stress*	*Mild water stress*	*Severe water stress*
0.2	38	11	2
2.0	47	42	21
6.0	46	45	28

Source: Sen-Gupta et al. 1989

Table 3 Concentration of Na^+ and K^+ (mmol kg^{-1} DW) in shoot and root of 19 days maize seedlings in response to salinity and potassium applications

		NaCl (1 mM)		NaCl (100 mM)	
		0.1 mM KNO_3	1 mM KNO_3	0.1 mM KNO_3	1 mM KNO_3
Shoot	K^+	630	1310	426	731
	Na^+	33.8	34.4	2128	1625
	K^+/Na^+ ratio	20.8	42.5	0.21	0.45
Root	K^+	396	689	630	813
	Na^+	89	72	1447	1203
	K^+/Na^+ ratio	4.48	9.82	0.44	0.68

Source: Botella et al. 1997

and cause Na toxicity and K deficiency in plants when low K level available in root medium (Zörb et al. 2005). Cell growth may also reduce due to leakage of K out of the cell under stress and lead to cell death. Salt stress limits essential nutrient transport from root to shoot (Termaat and Munus 1986) and lowers the net transport of different nutrients such as Ca^{2+}, NH_4^+, Mg^{2+} and mainly K^+ in plants. The plant tolerance mechanism is the selectivity of K ions over Na^+ (Cuartero et al. 1992) and also partially linked with a Na^+ concentration in leaf (Taleisnik and Grunberg 1994). Plants have the ability to adopt different mechanism to avoid entry of Na^+ reaching to leaves: controlling influx of Na^+ through root cells to plasmalemma (Jacoby and Hanson 1985); Na^+ sequestration into lower parts of the stem and root parenchyma cells and Na^+ removing from xylem streams (Johanson and Cheesman 1983) and Na^+ re-translocation via phloem from shoots to roots (Jacoby 1979). Decreased K supply in plants reduced the photosynthesis sharply due to disturbance in photosystem II (Chow et al. 1990). The higher requirement of K under 250 mM NaCl salt stress than lower salt stress level (50 mM NaCl) may not be ignored. Addition to K supply to roots at increased salt stress can ameliorate reductions in plant and shoot biomass and overwhelmed Na ion toxicity.

(c) Crop Lodging

Lodging is the stems displacement from upright position. Lodging may be partially disturbance or permanent, depends on extent of bending level of stem. Plants affected by two type of lodging: (a) shoot/stem lodging, lower culm internodes bending, (b) root lodging-root system disturbance cause crown leaning (Pinthus 1973) mainly occurs in cereals. Two stages are more critical for lodging, early grain development and heading stage for yield losses due to lodging. This may be due to the interactive factors of plant type, soil and environmental conditions and nutrient management strategies. Plant becomes susceptible for lodging because stem diameter was decreased in K-deficient plants. In K-deficient stem woody parenchyma and sclerenchyma fiber cell form poorly thin lignified cell walls which reduced its diameter (Mulder 1954; Wakhloo 1975). Optimum application of K fertilization increased sclerenchyma tissue layers thickness in rice (Vaithilingam and Balasubramanian 1976). Wheat internode cross section (Fig. 4a) shows that optimum K fertilization has improved thick stalk walls of plants. Improved stem thickness and stability associated with low senescing pith parenschyma and highly active plant defense mechanism with optimum K nutrition (Abney and Foley 1971). Addition of K fertilizer improves the growth of root length which ultimately supports the plant stand strengthening (Fig. 4).

K increased resistance against lodging in different crop species especially in rice (Datta and Mikkelsen 1985), corn (Welch and Flannery 1985; Csatho 1991), oilseed rape (Sharma and Kolte 1994) and wheat (Beaton and Sekhon 1985; Khurana and Bhaya 1990). Recently, Zaman et al. (2015) found that application of K fertilizer reduced the basal node length of rice plants, which is very supportive parameter to conclude the role of K fertilization in strengthening the stem strength.

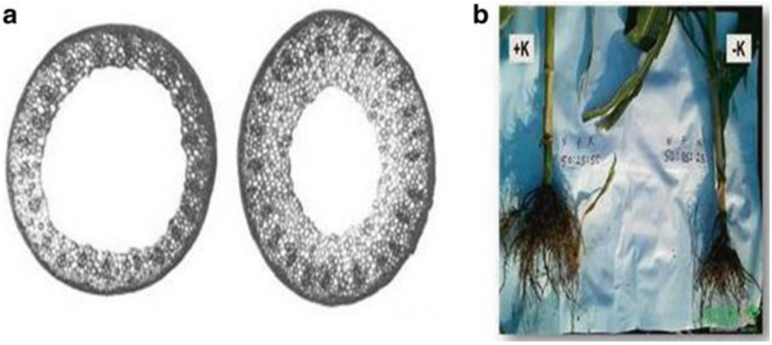

Fig. 4 Cross-section of 3rd internode of wheat plant with low (*left*) and high (*right*) K^+ nutrition (**a**), application of potash develop more intensive roots which may strengthen plant stand (**b**) (Source: Melis and Farina (1984) and International Potash Institute Switzerland)

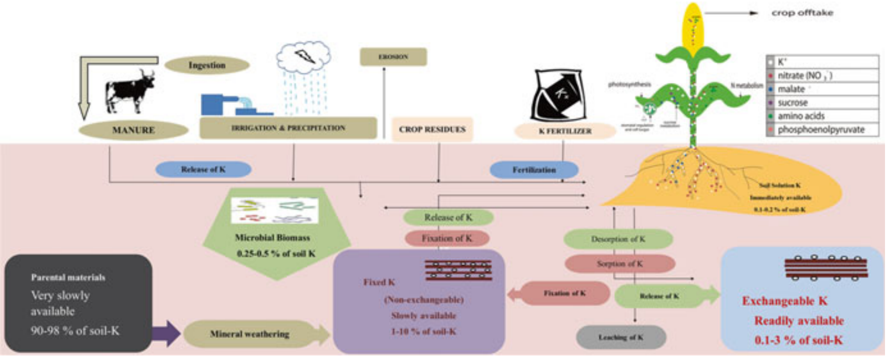

Fig. 5 Distribution of different forms of potassium in an agricultural system (modified from International Potash Institute Switzerland)

2.4 *Potassium for Sustainable Soil Fertility*

Potassium is present in soil in four distinctly different pools from where plants accessibility is differently and this should be considered while understanding the soil K availability to plants (Syers 2003). The conceptual understanding of K cycle in soil is illustrated in Fig. 5. Main pathway for K movement towards plants is via soil solution and soil solution K contributes only 5 % of total crop demand. In soil, it is about 0.1–0.2 % of the total soil K, however, this fraction is immediately available to the plants and replenished quicker than the exchangeable and non-exchangeable K pools. Exchangeable and non-exchangeable K make up about 1–2 % and 1–10 % of the total K respectively, and are the main contributors to K uptake by plants. Non-exchangeable form of K is slowly available to plants and is released from wedge sites of lattice weathered micaceous clay minerals (Mengel and Kirkby 2001). The main pool stock holds the bulk of K i.e. 90–98 % of the total soil K and release slowly because it is held in primary K bearing minerals structure. In Fig. 5 all possible sources of K have also been shown with their contribution to

K cycle. Although, the soils are considered very rich in K, however the available fraction is very low which is also decreasing very rapidly due to cultivation of high yielding crops. Potassium fertilizers need to be applied to soils to replenish the exchangeable K and non-exchangeable K for sustainable soil fertility, otherwise severe deficiency of K may occur which will not be easily cured because of strong interaction of K with soil minerals and huge quantity may be required to get response on crop growth (Wakeel et al. 2013).

3 Potassium and Human Health

Potassium is one of the electrolytes (chloride, calcium, magnesium, sodium and phosphorus) which play a very important role in human body. It is vital for optimum functioning of body cells, tissues and organs. Therefore, an optimum dose of K is required for human body on daily basis. According to the American National Academies of Food and Nutrition, an adequate intake of K is 4.7 g per person per day. Food enriched with K was always consumed by humans; however K mining from soils due to high yielding verities/hybrids and increased use of processed food which has removed the K from the food chain (He and MacGregor 2008). Furthermore, reduction in the consumption of fruits and vegetables has decreased the K in human food especially in developed countries. In developing countries less food availability and poor quality food based on less nutritive food has caused the issue of K deficiency in humans. Optimum use of K in human food has beneficial effects on human health (He and MacGregor 2008). Potassium normalizes the nerve and muscle functions and lowers the development of kidney stones due to reduced urinary Ca excretion. As K reduces the Ca excretion, therefore strengthen the bones. Diet containing sufficient K lowers the blood pressure decreasing the risk of cardio vascular diseases. Hypo serum K is causing glucose intolerance, and increasing K intake may prevent the development of diabetes (He and MacGregor 2008).

Peoples of developing/poor countries who have very less food diversity and low fruit and vegetables intake are even more susceptible to K deficiency. Use of fruits and vegetables rich in K can eliminate its deficiency in humans (Fig. 6). As also mentioned earlier, a very significant reason for such deficiency is also K depletion from soils due to high yielding intensive cropping without addition of K-fertilizers. Promoting biofortification of agricultural products through application of K fertilizers is essentially required for better human nutrition and its impact on human health.

4 Potassium Evaluation in Soils

Potassium evaluation in soils is like other nutrients and three standard methods are used which are based on time and resources available. These three evaluation processes includes visual observations, soil analysis and plant tissue analysis.

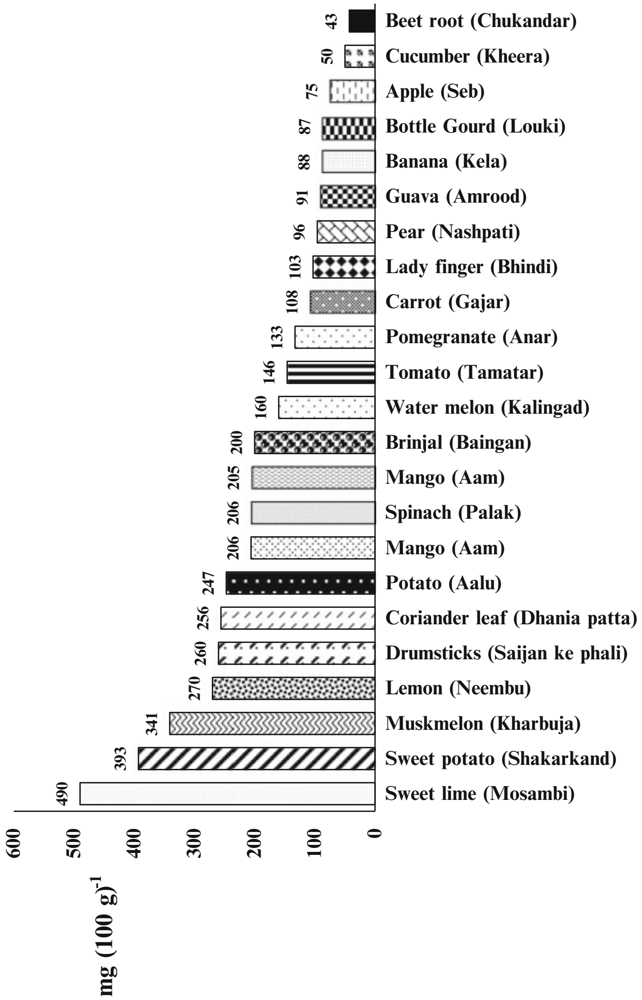

Fig. 6 Potassium concentration in fruits and vegetables (Source: National Institute of Nutrition, Hyderabad, India)

4.1 Visual Observations of Plants

Higher and lower concentrations of nutrients in soils lead to nutrient deficiencies and toxicities in plant which show unusual appearance which can be observed on plant leaves, stems or fruits. Generally, deficiency symptoms appears as stunted growth, interveinal chlorosis, chlorosis, red or purple discoloration and necrosis. However, to determine the deficiency or toxicity symptoms, it is necessary to understand essential role of nutrient and its mode of mobility in plant. Mobile nutrients deficiency symptoms first appear in older, lower leaves, whereas immobile nutrients deficiencies symptoms appear in younger, and upper leaves. Potassium is very mobile in plants, therefore its specific symptoms appears in older leaves first.

Plate 1 Chlorosis at old leaf margins of maize due to potassium deficiency (Source: International potash institute Switzerland)

Plate 2 Pottassium-deficiency symptoms due to sucrose accumulation in leaves of *Phaseolus vulgans* (Source: Cramer et al. 1994)

Chlorosis at the margins of older leaves appears firstly which leads to necrosis and ultimately cause plant tissue death (Plate 1).

As K is also involved in transport of sugar produced in leaves, therefore its deficiency may cause sucrose accumulation in leaves and typical symptoms may appear (Plate 2).

Deficiency symptoms of K are usually observed in early growth stages. In maize plant, at vegetative stage, K deficiency symptoms appear as brown or yellow leaf margins, however deficiency symptoms of K are difficult to recognize at harvest stages. At harvesting stages, maize shows some visual hints of K deficiency such as broken stalk, smaller cobs and unfilled cobs tips, which can be used to plan fertilizers for coming season.

Visual observation is diagnostic tool but not an authenticated method and can be limited by various factors, including pseudo deficiencies and hidden hunger. Therefore, plant and soil analytical testing is crucial to verify soil nutrient status and nutrient stress symptoms. Visual symptoms evaluation in field is quick and an inexpensive method to identify or detect deficiency or toxicity of nutrients in crops.

4.2 Soil Testing

Soil testing is a quantitative analysis of soil for its physicochemical properties. Soil analysis gives the precise amount of all nutrients; however the methods of analysis may be different for different elemental analysis. Good soil test report is much dependent on a truly representative soil sample. If soil seems homogeneous, one representative sample may be sufficient, but when abnormal growth areas present, then one sample must be taken from the normal area and from the problem area, each. Potassium is extracted from soils generally by NH_4-acetate method which includes the water soluble and NH_4 replaceable K in the soil, which are considered as readily available forms of K. The other method used is ammonium bicarbonate diethylene triamine penta acetic acid (AB-DTPA) method which also includes exchangeable and water soluble K; however its value is relatively lower than NH_4-acetate exchangeable K.

Usually, when K is less than 150 mg Kg^{-1}, it is classified as low K and K concentration in range between 250 and 800 ppm is considered high to excessive. However, soils are much diverse and crop response to K fertilizers is variable even at optimum K levels because of a close relation of K to soil minerals plants can reveal deficiencies. Along with soil-K concentration, K-fixing capacity of soils and soil mineralogy should also be considered while recommending potassic fertilizers.

4.3 Plant-Tissue Analysis

In the nineteenth century, several elements were recognized as essential nutrients for plant growth by different scientists. Justus von Liebig and later on others scientist started to analyze mineral contents in plants. The idea was conceived by Weinhold (1862) to analyze plant to determine the available nutrient supply. Goodall and Gregory (1947) concluded that much of the work done prior to 1947 could be classified into one of four categories in terms of research as well as plant analysis utility in crop production. These are categorized as: (a) To detect nutritional disorder caused by certain deficiency symptoms, (b) Field trials results interpretation, (c) Use of advanced testing methods for advisory work, (d) Plant analysis for interpretation of nutritional survey.

Plant analysis of different parts is a valuable service for crop management practices. Alone, this makes proper fertilizer recommendation used for certain crops, fruit trees and also for grapes. Plant tissue analysis and soil testing in combination is a best approach for detecting nutrient deficiency symptoms and fertilizer recommendations. Plant analysis alone is not a substitute of soil testing method but plant tissue analysis is more effective in conjunction with soil analysis. Several environmental and soil characteristics contribute soil fertility and influence nutrient uptake in plant. These factors herbicide damage, soil pH, drought, waterlogging, air temperatures, diseases, insects, soil compaction etc. can reduce the nutrient uptake by plants, therefore only addition of deficient nutrient in soil may not tell the true availability of nutrients to plants. Plant tissue analysis represent the actual availability of nutrients to plants. Plant analysis is also useful tool when small field area is discolored or show stunted growth.

K concentration in plant tissues can be determined from fresh material, (i.e. plant tissue analysis), and also from total dry plant matter. This test is basically qualitative method and appropriately quick for growing crops. Two methods for tissue analysis are used that are wet digestion and dry-ashing. Dry-ashing is simple digestion method, less expensive and non-hazardous as compared to wet digestion with HNO_3-$HClO_4$. Plant analysis with dry ashing for Ca, Mg, Na, P and K. Different micronutrients cations (Zn, Mn, Cu and Fe) can also be determined by dry-ashing method but sophisticated for low silica contents crops (legumes). The wet digestion with HNO_3-$HClO_4$ is required for micronutrient full recovery method in that plant tissue which has high silica contents (like barley, wheat, sugarcane and rice etc.).

After digesting the plant sample, K concentration can easily be detected by flame photometer. The general optimum concentration in plant sample is >1.5 % dry plant materials, however the actual optimum concentration varies with plant species. The optimum concentration in different plant species is given in Table 4.

5 Conclusion and Recommendations

Role of K in crop growth and yield development is clear; however the K fertilization may not be required at all agricultural sites because deficiency of K may not be observed at all agricultural sites. However, there is a need to ensure the site-specific balanced fertilization based on soil analysis. Application of K fertilizers should be dealt more aggressively because in addition to direct crop-growth promoting effects, it also improves the nutrient use efficiency of plants and better N use efficiency has been observed at K fertilized agricultural sites. As K has ameliorating effects under various environmental stresses, such as drought, salinity and lodging, therefore this aspect should be more highlighted. Soils are being mined for K due to its higher concentrations in harvested crop parts, the removal of available K must be replenished for agricultural sustainability. In human and animal nutrition K has significant role and its deficiency in humans can cause cardiovascular and nervous diseases. The ultimate source of K in human nutrition is the soil which provides K to plants

Table 4 Sufficient range of K concentration in plant parts for optimum plant growth

Plant species	Concentration range (mg K/g DM)
Cereals, young shoot 5–8 cm above soil surface	
Wheat (*Triticum aestivum*)	35–55
Rice (*Oryza sativa*)[a] before anthesis	20–30
Oat (*Avena sativa*)	45–58
Barley (*Hordeum vulgare*)	35–55
Maize (*Zea mays*)[a]	20–35
Rye (*Secale cereale*)	28–45
Dicotyledonous field crops	
Forage and sugar beets (*Beta vulgaris*)	35–60
Sunflower (*Helianthus annuus*)[a] at anthesis	30–45
Potato (Solanum tuberosum)[a] at flowering	50–66
Soya bean (*Glycine max*)	25–37
Phaseolus beans (*Phaseolus vulgaris*)	20–30
Cotton (*Gossypium*) anthesis to fruit setting	17–35
Rape (*Brassica napus*)[a]	28–50
Forage Crops	
Total shoot at flowering 5 cm above soil surface, Dactylis glomerata, Poa pratensis, Phleum pratensis, Lolium perenne, Festuca pratensis	25–35
Vegetables	
Lettuce (*Lactuca sativa*)[a]	42–60
Spinach (*Spinacia oleracea*)	35–53
Pepper (*Capsicum annuum*)[a]	40–54
Watermelon (*Cirulus vulgaris*)[a]	25–35
Tomatoes (*Lycopersicon esculentum*)[a] at first fruit setting	30–40
Onions (*Allium cepa*) at mid vegetation stage	25–30
Carrot (*Daucus carota sativus*)[a]	27–40
Asparagus (*Asparagus officinalis*) fully developed shoot	15–24
Berry fruits[a]	
From anthesis until fruit maturation *Fragaria ananassa*, *Rubus idaeus*, *Ribes rubrum*, *Ribes nigrum*, *Ribes grossularia*	18–25
Miscellaneous crops	
Tea (*Camellia sinensis*)[a] at the mid of the vegetation season	16–23
Tobacco (*Nicotiana tabacum*)[a] at the mid of the vegetation season	25–45
[a]Young fully developed leaf	

Source: W. Bermann, *Nutritional Disorders of Crop Plants*. VEB Gustav Fischer Verlag,. Jena 1986

and is then used by humans and animals. In a developing world, it is required to optimize the K concentration in staple crops to fulfill the nutritional needs. Precise recommendation of K is very critical as K has strong interactions with clay minerals, therefore, while recommending K fertilizers soil minerals should be considered for better agricultural returns; otherwise plants may not respond to K fertilizers due to its unavailability to plants.

References

Abd-Alla MH, Wahab AMA (1995) Response of nitrogen fixation, nodule activities, and growth to K supply in water-stressed broad bean. J Plant Nutr 18:1391–1402

Abd-El-Motagally F (2004) Evaluation of two sugar beet cultivars (*Beta vulgaris* L.) for growth and yield under drought and heat conditions. PhD thesis. Faculty of Agricultural and Nutritional Sciences, Home Economics and Environmental Management, Justus Liebig University, Giessen

Abdi M, Nour-Mohamedi G, Golchin A (2002) The influence of foliar nutrition of urea and potassium chloride on grain yield, grain protein content, yield components and leaf relative water content of sardari wheat under rain-fed conditions. J Agric Sci Islamic Azad Univ 8:29–38

Abney TS, Foley DC (1971) Influence of nutrition on stalk rot development of *Zea mays*. Phytopathology 61:1125–1129

Ache P, Becker D, DeekenR DI, Weber H, Fromm J, Hedrich J (2001) VFK1, a Vicia faba K^+ channel involved in phloem unloading. Plant J 27:571–580

Ahmad P, Ashraf M, Hakeem KR, Azooz MM, Rasool S, Akram NA (2013) Potassium starvation-induced oxidative stress and antioxidant defense responses in *Brassica juncea*. J Plant 9(1):1–9

Allen VB, David J (2007) Handbook of plant nutrition. Pilbeam (eds). CRC Press, 600 Broken Sound Parkway NW, Suite 300, Boca Raton, FL 33487. 613 p, $139.95 hardcover. ISBN 0-8247-5904-4

Amtmann A, Sanders D (1999) Mechanism of Na^+ uptake by plant cells. Adv Bot Res 29:75–112

Amtmann A, Troufflard S, Armengaud P (2008) The effect of potassium nutrition on pest and disease resistance in plants. Physiol Planta 133:682–691

ArabiMIE MN, Jawhar M (2002) Effect of foliar and soil potassium fertilization on wheat yield and severity of septoria tritici blotch. Aust Plant Pathol 31:359–362

Beaton JD, Sekhon GS (1985) Potassium nutrition of wheat and other small grains. In: Munson RD (ed). Potassium in agriculture ASA, Madison

Bergmann E, Bergmann HW (1985) Comparing diagrams of plant/leaf analysis presenting by rapid inspection the mineral nutrient element status of agricultural crop plants. Potash Rev. Sub. 5 No. 2/1985 pp 1–10

Berkowitz GA, Kroll KS (1988) Acclimation of photosynthesis in *Zea mays* to low water potentials involves altered degree of protoplast volume reduction. Planta 175:374–379

Berkowitz GA, Peters JS (1993) Chloroplast inner-envelope ATPase acts as a primary H^+ pump. Plant Physiol 102:261–267

Bhatti AU, Wadud A, Shah GS (1981) Response of some major cereals of NWFP to nitrophos and nitrophoska complex fertilizers. Rice J Agric Res Pak 19:163–167

Bohn HL, Mcneal LB, O'connor AG (2001) Soil chemistry, 3rd edn. Wiley, New York/Chi Chester/Toronto/Singapore, p 120

Bohra JS, Doerffling K (1993) Potassium nutrition of rice (*Oryza sativa* L.) varieties under NaCl salinity. Plant Soil 152:299–303

Bolwell GP, Wojtaszek P (1997) Mechanisms for the generation of reactive oxygen species in plant defence: a broad perspective. Physiol Mol Plant Pathol 51:347–366

Botella MA, Martinez V, Pardines J, Cerda A (1997) Salinity induced potassium deficiency in maize plants. J Plant Physiol 150:200–205

Cakmak I (1994) Activity of ascorbate-dependent H_2O_2-scavenging enzymes and leaf chlorosis are enhanced in magnesium and potassium deficient leaves, but not in phosphorus deficient leaves. J Exp Bot 45:1259–1266

Chow WS, Marylin CB, Anderson JM (1990) Growth and photosynthetic responses of spinach to salinity: implications of K^+ nutrition for salt tolerance. Aust J Plant Physiol 17:563–578

Cox AE, Joern BC, Brounder SM, Gao D (1999) Plant-available potassium assessment with a modified sodium tetraphenylboron method. Soil Sci Soc Am J 63:902–911

Cramer GR, Lauchli A, Polito VS (1985) Displacement of Ca^{2+} from the plasmalemma of root cells. Plant Physiol 79:211–297

Cramer GR, Lynch J, Lauchli A, Epstein E (1987) Influx of Na^+, K^+ and Ca^{2+} into roots of salt-stressed cotton seedlings. Plant Physiol 83:510–516

Cramer GR, Alberico GJ, Schmidt C (1994) Salt tolerance is not associated with the sodium accumulation of two maize hybrids. Aust J Plant Physiol 21:675–692

Csatho P (1991) Effect of NPK-fertilization and split application of nitrogen on lodging due to windstorm and harvestable grain yield of maize. Acta Agron Hung 40:281–294

Cuartero J, Yeo AR, Flowers TJ (1992) Selection of donors for salt tolerance in tomato using physiological traits. New Phytol 121:63–69

Datta SK, Mikkelsen DS (1985) Potassium nutrition of rice. In: Munson RD (ed) Potassium in agriculture. ASA, Madison

Davis JG, Walker ME, Parker MB, Mullinix B (1996) Long term phosphorus and potassium application to corn on coastal plain soils. J Prod Agric 9:88–94

Doll EC, Lucas RE (1973) Testing soils for potassium, calcium, and magnesium. p 133–151. In: Walsh LM, Beaton JD (eds). Soil testing and plant analysis. Soil Science Society of America, Madison, Wisconsin

Dreyer I, Uozumi N (2011) Potassium channels in plant cells. FEBS J 278:4293–4303

Egilla JN, Davies FTJ, Drew MC (2001) Effect of potassium on drought resistance of Hibiscus rosa-sinensis cv. Leprechaun: plant growth, leaf macro and micronutrient content and root longevity. Plant Soil 229:213–224

e-ifc No. 13. 2007. Improving the efficiency of nitrogen use with potassium: De-Bottlenecking nitrogen use efficiency through balanced fertilization and adequate supply of potassium. International Potash Institute, Switzerland. http://www.ipipotash.org/eifc/2007/13/2/

Engels C, Marschner H (1992) Adaptation of potassium translocation into the shoot of maize (*Zea mays* L.) to shoot demand: evidence for xylem loading as a regulating step. Physiol Planat 86:263–268

Fernando M, Mehroke J, Glass DM (1992) De novo synthesis of plasma membrane and tonoplast polypeptides of barley roots during short-term K^+ deprivation. In search of the high-affinity K^+ transport system. Plant Physiol 100:1269–1276

Flowers T, Troke PF, Yeo AR (1977) The mechanisms of salt tolerance in halophytes. Annu Rev Plant Physiol 28:89–121

Ford CW, Wilson JR (1981) Changes in levels of solutes during osmotic adjustment to water stress in leaves of four tropical pasture species. Aust J Plant Physiol 8:77–91

Gajdanowicz P, Michard E, Sandmann M, Rocha M, Correa LGG, Ramìrez-Aguilar SJ (2011) Potassium (K^+) gradients serve as a mobile energy source in plant vascular tissues. Proc Natl Acad Sci U S A 108:864–869

Gerendas J, Heuser F, Sattelmacher B (2007) Influence of Nitrogen and Potassium Supply on Contents of Acrylamide Precursors in Potato Tubers and on Acrylamide Accumulation in French Fries. J Plant Nutr 30:1499–1516

Gething PA (1990) Potassium and water relationships. In: Potash facts. IPI, Bern

Goodall DW, Gregory PG (1947) Chemical composition of plants as an index of their nutritional status. Imperial Bureau Horticultural Plantation Crops. Technical Communication No. 17. Ministry of Agriculture, London, England

Gregory PJ, Crawford DV, McGowan M (1979) Nutrient relations of winter wheat. 1. Accumulation and distribution of Na, K, Ca, Mg, P, S and N. J Agric Sci Camb 93:485–494

Havlin JL, Beaton JD, Tisdale SL, Nelson WL (1999) Soil Fertility and Fertilizers, 6th edn. Prentice Hall, Upper Saddle River, 499 p

He FJ, MacGregor GA (2008) Beneficial effects of potassium on human health. Physiol Plant 133:725–735

Hsiao TC, Lauchli A (1986) Role of potassium in plant-water relations. In: Tinker B, Lauchli A (eds) Advances in Plant Nutrition, vol 2. Praeger Scientific, New York, pp 281–312

Humble GD, Raschke K (1971) Stomatal opening quantitatively related to potassium transport. Plant Physiol 48:447–453

Hussain F, Yasin M (2003) Soil Fertility monitoring and management in rice-wheat system. Ann. Report LRRP, NARC, Islamabad. pp 1–16

Int'l Potash Instt, 1986. Effect of potash in long term experiments. Int'l Fertilizer Correspondent 27:3–4

Itoh R, Kumara A (1987) Acclimation of soybean plants to water deficit. V. Contribution of potassium and sugar to osmotic concentration in leaves. Jpn J Crop Sci 56:678–684

Jacoby B (1979) Sodium recirculation and loss from Phaseolus vulgaris L. Ann Bot 43:741–744

Jacoby B, Hanson JB (1985) Controls on $^{22}Na^+$ influx in corn roots. Plant Physiol 77:930–934

Johanson JG, Cheesman JM (1983) Uptake and distribution of sodium and potassium by corn seedlings. I. Role of the mesocotyl in "sodium exclusion". Plant Physiol 73:153–158

Jones RG, Pollard A (1983) Proteins, enzymes and inorganic ions. In: Läuchli A, Bieleski RL, (ed) Inorganic plant nutrition. Springer; New York, pp 528–562

Kafkafi U (1990) The functions of plant K in overcoming environmental stress situations. In: Proceedings of the 22nd colloquium of IPI, pp 81–93, held in Soligorsk, USSR, IPI, Bern

Kafkafi U (1991) Root growth under stress. In: Waisel Y, Eshel A, Kafkafi U (eds). Plant roots, the hidden half. Marcel Dekker, Inc. New York, pp 375–391

Khattak JK, Bhatti AU (1986) Coop. Res. Prog, National out reach Res. Project, Soil. Fertility and Fertilizer use in Pakistan. Deptt. of Soil Sci. N.W.F.P. Agric. Univ. Peshawar. pp 60–69.

Khurana GP, Bhaya GP (1990) Effect of potash on wheat irrigated with nitrate waters. Ind J Agron 35:429–431

Krishnan KS (1977) Response of high yielding varieties of wheat to fertilizer application with special reference to potassium. Exp Agric 13:337–340

Kuchenbuch R, Jungk A (1984) Z Pflanzenernahr Bodenkd 147:435–448

Lamb C, Dixon RA (1997) The oxidative burst in plant disease resistance. Annu Rev Plant Physiol Plant Mol Biol 48:251–275

Leigh RA (2001) Potassium homeostasis and membrane transport. J Plant Nutr Soil Sci 164:193–198

Leigh RA, Jones RGW (1984) A hypothesis relating critical potassium concentrations forgrowth to the distribution and functions of this ion in the plant cell. New Phytol 97:1–13

Leigh RA, Jones RGW (1986) Cellular compartmentation in plant nutrition: the selective cytoplasm and the promiscuous vacuole. In: Tinker B, Lauchli A (eds) Advances in plant nutrition 2. Praeger Scientific, New York, pp 249–279

MacRobbie EAC (1977) Functions of ion transport in plant cells and tissues. MTP Int Rev Sci 13:211–247

Marschner H (1995) Mineral Nutrition of Higher Plants: functions of macronutrients. San Diego, USA

Marschner P (2012) Marschner's mineral nutrition of higher plants. 3rd ed. Academic Press, London, pp 178–189

Marschner H, Krauss A (1980) Correlations between potassium content and quality of potatoes. Kartoffelbau 131:65–67

Melis M, Farina MPW (1984) Potassium effects on stalk strength, premature death and lodging of maize (Zea mays L.). S Afr J Plant Soil 1:122–124

Mengel K (2001) Principles of plant nutrition. 5th edn. Kluwer Academic Publishers; Dordrecht, the Netherlands, pp 481–509

Mengel K, Haeder HE (1977) Effect of potassium supply on the rate of phloem sap exudation and the composition of phloem sap of *Ricinus communis*. Plant Physiol 59:282–284

Mengel K, Kirkby EA (2001) Principles of plant nutrition. Kluwer Academic Publishers, Dordrecht

Mesbah EAE (2009) Effect of irrigation regimes and foliar spraying of potassium on yield, yield components and water use efficiency of wheat (*Triticum aestivum* L.) in sandy soils. World J Agric Sci 5:662–669

Miller C (1993) Potassium selectivity in proteins - oxygen cage or pi in the face. Science 261:1692–1693

Moran N, Ehrenstein G, Iwasa K, Mischke C, Bare C, Satter RL (1988) Potassium channels in motor cells of Samanea saman. A patch clamp study. Plant Physiol 88:643–648

Mpelasoka BS, Schachman DP, Treeby MT, Thomas MR (2003) A review of potassium nutrition in grapevines with special emphasis on berry accumulation. Aust J Grape Wine Res 9:154–168

Mulder EG (1954) Effect of mineral nutrition on lodging of cereals. Plant Soil 5:245–306

Nandwal AS, Hooda A, Datta D (1998) Effect of substrate moisture and potassium on water relations and C, N and K distribution in *Vigna radiata*. Biol Planata 41:149–153

Nunes MA, Correia MM, Lucas MD (1983) NaCl-stimulated proton efflux and cell expansion in sugar beet leaf discs. Planta 158:103–107

Perrenoud S (1990) Potassium and plant health. 2nd edn. International Potash Institute; Bern, Switzerland: 1990. pp 8–10

Pettigrew WT (2008) Potassium influences on yield and quality production for maize, wheat, soybean and cotton. Physiol Plant 133:670–681

Pier PA, Berkowitz GA (1987) Modulation of water stress effects on photosynthesis by altered leaf K^+. Plant Physiol 85:655–661

Pinthus MJ (1973) Lodging in wheat, barley and oats: the phenomenon, its causes and preventive measures. Adv Agron 25:209–263

Prabhu AS, Fageria NK, Huber DM, Rodrigues FA (2007) Potassium and Plant Disease. In: Datnoff LE, Elmer WH, Huber DM (eds) Mineral Nutrition and Plant Disease. American Phytopathological Society, St. Paul, pp 57–78

Premachandra GS, Saneoka H, Ogata S (1991) Cell membrane stability and leaf water relations as affected by potassium nutrition of water-stressed maize. J Exp Bot 42:739–745

Rehman H, Bhatti AU, Gurmani AH (1982) Fertilizer experiments on cereal crops in D.I.Khan district. Soil. Sci. Div. Agric. Res. Instt. Tarnab, Peshawar. 36 p

Roberts SK, Tester M (1997) Permeation of Ca^{2+} and monovalent cations through an outwardly rectifying channel in maize root stelar cells. J Exp Bot 48:839–846

Rus A, Yokoi S, Sharkhuu A, Reddy M, Lee BH, Matsumoto TK, Koiwa H, Zhu JK, Bressan RA, Hasegawa PM (2001) AtHKT1 is a salt tolerance determinant that controls Na^+ entry into plant roots. Proc Natl Acad Sci U S A 98:14150–14155

Schubert S (2006) Pflanzenern¨ahrung. Verlag Eugen Ulmer, Stuttgart

Scott AD, Smith SJ (1987) Sources, amount and forms of alkali elements in the soil. Adv Soil Sci 6:101–147

Sen-Gupta A, Berkowitz GA, Pier PA (1989) Maintenance of photosynthesis at low leaf water potential in wheat. Plant Physiol 89:1358–1365

Shabala S (2003) Regulation of potassium transport in leaves: from molecular to tissue level. Ann Bot 92:627–634

Shabala S, Babourina O, Rengel Z, Nemchinov LG (2010) Non-invasive microelectrode potassium flux measurements as a potential tool for early recognition of virus–host compatibility in plants. Planta 232:807–815

Sharma SR, Kolte SJ (1994) Effect of soil-applied NPK fertilizers on severity of black spot disease (*Alternaria brassicae*) and yield of oilseed rape. Plant Soil 167:313–320

Sharma KD, Nandwal AS, Kuhad MS (1996) Potassium effects on CO_2 exchange, ARA and yield of cluster bean cultivars under water stress. J Pot Res 12:412–423

Siddique T, Aslam J, Alyas M (1997) Response of wheat to potassium application in different soil series of Punjab. Pak J Soil Sci 13:92–96

Smith JAC, Milburn JA (1980) Phloem turgor and regulation of sucrose loading in *Ricinus communis* L. Planta 148:42–48

Somers TC (1977) A connection between potassium levels in the harvest and relative quality in Australian red wines. Aust Wine Brew. Spirit Rev 96:32–34

Syers JK (2003) Potassium in soils: current concepts. In: Johnston AE (ed) Proceedings of the IPI Golden Jubilee congress 1952–2002 held in Basel, Switzerland 8–10 October 2002. Feed the Soil to Feed the People. The Role of Potash in Sustainable Agriculture. International Potash Institute, Switzerland. p 301–310

Taiz L, Zeiger (2006) Plant physiology, Fourth Edition. Sinauer Associates. Sunderland, MA. 764 pages

Taleisnik E, Grunberg K (1994) Ion balance in tomato cultivars differening in salt tolerence. I. Sodium and potassium accumulation and fluxes under moderate salinity. Physiol Planat 92:528–534

Termaat A, Munus R (1986) Use of concentrated macronutrient solutions to separate osmotic from NaCl-specific effects on plant growth. Aust J Plant Physiol 13:509–522

Tisdale S, Nelson WL, Beaton JD, Havlin JL (1993) Soil Fertility and Fertilizers, 5th edn. MacMillan Publishing Company, New York

Vaithilingam C, Balasubramanian M (1976) Effect of potash on sclerenchyma thickness and silica content in rice. Indian Potash J 1:17–23

Wakeel A, Hanstein S, Pitann B, Schubert S (2010) Hydrolytic and pumping activity of H^+-ATPase from leaves of sugar beet (*Beta Vulgaris* L.) as affected by salt stress. J Plant Physiol 167:725–731

Wakeel A, Gul M, Sanaullah M (2013) Potassium dynamics in three alluvial soils differing in clay contents. Emir J Food Agric 25:39–44

Wakhloo JL (1975) Studies on the growth, flowering and production of female sterile flowers as affected by different levels of foliar potassium in *Solanum sisymbrifolium* Lam. J Exp Bot 26:425–450

Weinhold A (1862) Analyze von unkiauterm des bodens der versuchsstation chemnitz. Landeo Vers Sta 4(188–1):93

Welch LF, Flannery RL (1985) Potassium nutrition of corn. In: Munson RD (ed) Potassium in agriculture. ASA, Madison

Yadav DS, Goyal AK, Vats BK (1999) Effect of potassium in *Eleusine coracana* (L.) Gaertn. under moisture stress conditions. J Pot Res 15:131–134

Zaman U, Ahmad Z, Farooq M, Saeed S, Ahmad M, Wakeel A (2015) Potassium fertilization may improve stem strength and yield of basmati rice grown on nitrogen-fertilized soils. Pak J Agric Sci 52:439–445

Zhang YH, Cheng H, Alexeenko VA, Dempsey CE, Hancox (2010) Characterization of recombinant hERG K^+ channel inhibition by the active metabolite of amiodarone desethyl-amiodarone. J Electrocardiol 43:440–448

Zörb C, Noll A, Karl S, Leib K, Yan F, Schubert S (2005) Molecular characterization of Na^+/H^+ antiporters (ZmNHX) of maize (*Zea mays* L.) and their expression under salt stress. J Plant Physiol 162:55–66

Zörb C, Senbayram M, Peiter E (2014) Potassium in agriculture, Status and perspectives. J Plant Physiol 171:656–669