Ameliorative effect of potassium sulphate on the growth and chemical composition of wheat (*Triticum aestivum* L.) in salt-affected soils

Z. Hussain[1] , R.A. Khattak[2], M. Irshad[3*] and A.E. Eneji[4]

[1]Department of Development Studies, COMSATS Institute of Information Technology, Abbottabad, Pakistan. [2]CECOS University of Engineering and Emerging Sciences, Peshawar, Pakistan.[3]Department of Environmental Sciences, COMSATS Institute of Information Technology, Abbottabad, Pakistan.[4]Department of Soil Science, University of Calabar, Nigeria.[*]Corresponding author: mirshad@ciit.net.pk.

Abstract

Potassium (K) and sodium (Na) coexist on the soil exchange complex and soil solution. Both cations may exert antagonistic or synergistic effects on mutual absorption and translocation within plants, particularly under saline and saline-sodic field conditions. This study investigated the role of K in alleviating the adverse effects of Na on wheat [*Triticum aestivum* (L), Iquilab-91] grown at two fields sites varying in salinity. The soils were moderately calcareous, weakly structured, mixed hyperthermic Typic Haplustepts. Site 1 was silty clay loam saline-sodic soil (ECe = 4.23-9.45 dS m^{-1}) irrigated with groundwater with an EC_{iw} value of 5.0 dSm^{-1} ; Site 2 was clay loam saline soil (ECe = 3.2-5.0 dS m^{-1}) irrigated with groundwater with an ECiw of 2.4 dS m^{-1}. Both sites were treated with 0, 50 and 100 kg K ha^{-1} applied as K_2SO_4 (41% K) fertilizer. Significant increases of 14 and 30% in grain yield were measured at both sites, and 35 and 54% increase in dry matter yields were observed in clay loam soil with the application of 50 and 100 kg K ha^{-1}. Potassium application decreased leaf [Na] and significantly increased [K]; the K:Na ratio showed a positive correlation with yield. Soil analysis showed significant increases in [K], [Na] and SAR, while pH, ECe and [Ca+Mg] were not affected by the K fertilizer. The K_2SO_4 increased crop yield by mitigating the adverse effect of Na and would thus be an effective source of K for crop production in saline and saline-sodic soils.

Keywords: Potassium sulphate, salt-affected soils, K: Na, leaf tissue composition, wheat

Abbreviations: ECiw, Electrical conductivity of irrigation water; Ece, Electrical conductivity of extract; K, Potassium; Ca, Calcium; Mg, Magnesium; Na, Sodium; SAR, Sodium adsorption ratio.

1. Introduction

Salinity and sodicity are soil conditions that mostly occur in arid and semi-arid regions. In soils of arid zones, there is increased potential for hazardous accumulation of salts and the productivity of crops and plants is severely limited under such conditions. Reclamation of salt-affected soils through tillage, water, crop and chemical and/or fertilizer amendment practices is an increasingly important tool for improving crop productivity in many areas of the world (Jordan *et al.*, 2004). The reclamation of these soils has been a driving force to turn marginally arable areas to agriculturally productive land by reducing levels of salinity and exchangeable Na.

Reduction in crop yield in saline and saline-sodic soils is associated with osmotic and specific ion effect and the degree and extent of the adverse effect is further exacerbated when saline water is used for irrigation (Bernstein, 1975; Sharma and Rao, 1998). Potassium (K) plays an important role in mitigating the adverse effects of high salt concentrations in soils (Garg and Gupta, 1998) and the stress tolerance of crops can be enhanced by optimizing K nutrition (Römheld and Kirkby, 2010). Potassium is known for its role in osmo-regulation and stress mitigation, particularly in saline conditions (Cakmak, 2010). Under saline-sodic soil conditions, K interactions with Na in the distribution between soil solution and exchange phases and in subsequent absorption by roots and translocation within plants could be more critical.

Various studies with wheat have shown yield increases in responses to K fertilization in salt-affected soils. Genotypic differences for salt tolerance among the crop varieties are often explained on the variety's ability to exclude Na from root with least imbalance in K uptake (Schachtman and Liu, 1999). In these cases the salt tolerant varieties show a lower Na:K ratio throughout a wide range of saline conditions (Sherif *et al.*, 1998; Hussain and Khattak, 2005). Garg and Gupta (1998) correlated the maintenance of sufficient Ca and K concentrations and wider K:Na ratios in the tissues under saline conditions with higher salt tolerance in mustard and suggested that such interactions deserve further investigation. The Egyptian wheat variety, Sakha 92 showed the best response to additional K at low and high NaCl concentrations (Sherif *et al.*, 1998). The study also suggested that under low saline conditions, there is no need for K addition while at high level of salinity, application of K fertilizers could be useful to mitigate the adverse effects of salinity and/or sodicity on wheat growth in arid and semi-arid regions.

Most of the salinity-nutrient interaction studies have been conducted in sand or solution cultures (e.g, Grattan and Grieve, 1994; Grattan and Grieve, 1999; Silberbush and Ben-Asher, 2001) wherein the nutrient and salt concentrations were easily controlled. The ionic interactions in soilless system are simple and easily understood as compared to the complex system of soil and plants, particularly under saline environment (Khattak and Jarrell, 1988; Silberbush and Ben-Asher, 2001). Furthermore, the ratios of nutrients in solution culture are much different from those experienced by plants under field conditions (Grattan and Grieve, 1999), involving interactions and competition amongst different ions for adsorption sites on soil solid phase and for absorption sites on roots surfaces (Comerford, 2005; Fageria *et al.*, 2011). Under field conditions, several factors such as CEC and amount and type of clay and organic matter affect the bio-availability of K (Tisdale *et al.*, 1985). For, instance, fine textured soils have high CEC and hold high exchangeable K and may cause slow release of available K. Cao *et al.* (1991) concluded that the application of K fertilizer increased the movement of K from soil to root-surface and improved the availability of K to wheat roots.

Salinity and fertility interaction experiments conducted under saline field environment showed an improved crop yield by addition of fertilizer to soil irrigated with saline water (Hussain and Khattak, 2005; Muhammad and Khattak, 2009). A more systematic research is required to observe the responses of crops to added K at the field level where extreme variability in salinity, soil texture and soil nutritional status is a norm. Here, we studied the effects of K fertilization on grain and dry matter yields, leaf tissue chemical composition and K: Na ratio in relation to the physico-chemical properties of post-harvest saline and saline-sodic soils irrigated with saline groundwater of variable salinities.

2. Materials and Methods

Wheat [*Triticum aestivum* (L.), var. Inqilab-91] was grown on farmer's fields at two sites in Lachi (Kohat) area of Pakistan to evaluate the effect of potassium fertilizer in salt affected soils. Kohat District is 70 km from Peshawar. The area lies between longitude 320 47' and 340 5' North and latitude 690 53' and 720 1' East and falls in the semi-arid and sub-humid subtropical continental category of climate classification (Soil Survey of Pakistan, 2007). Lachi lies 33°23́ 43″ N and the soils are reddish brown or yellowish brown, moderately calcareous, ranging from fine sandy loam to silty clay and clay loams. The soils are weakly structured and are classified as mixed hyperthermic Typic Haplustepts (Soil Survey of Pakistan, 2007). Parent rock material of the district Kohat is comprised of sandstone, limestone conglomerates, and salt rocks. The water reservoirs underlying the area are deep and contain poor quality, saline water with adverse effecton crop yield. Site 1 was a silty clay loam saline-sodic (ECe= 4.2-9.5 dS m^{-1}; pH1:5= 8.2-8.9) soil, irrigated with groundwater having ECiw = 5.0 dSm^{-1}. Site 2 was a clay loam saline (ECe = 3.2-5.0 dS m^{-1}; pH1:5=7.6-8.1) soil, irrigated with groundwater having ECiw= 2.4 dS m^{-1} (Table 1).

2.1. Experimentation

For each site, potassium was applied at 0, 50 and 100 kg K ha^{-1} in the form of potassium sulfate (K_2SO_4) along with basal doses of urea (120 kg N ha^{-1}) and triple super phosphate (TSP) (90 kg P ha^{-1}). The treatments (K levels) were replicated three times at each site and arranged into a randomized complete block design. After 3-4 days of groundwater irrigation, fields were chisel-ploughed and harrowed. The experimental plot at each site was divided into 9 plots of 3 x 3 m2 with plot to plot distance of 1 m. Alleyways between plots were developed into water channels to provide irrigation. After the application of treatments, wheat cv. Inquilab 91 was sown in November at the seed rate of 120 kg ha^{-1} and harvested in April. The average rainfall during the cropping months was 400 mm, while relatively higher mean rainfall was received during February and March. Mean monthly maximum temperatures ranges from 17.5 to 30.6 oC and minimum from 5.2 to 12 oC during the cropping period (Soil Survey of Pakistan, 2007a). All agronomic practices such as weeding and pest control were done according to local practices.

2.2. Sampling and sample processing

Groundwater samples were collected from the wells on the farmers' fields at both sites before irrigation. Pre-cultivation and post harvest composite soil samples (0-30 m depth) from each site and youngest fully mature wheat leaf samples were also collected before harvesting.

After air-drying, the soil samples were gently crushed, sieved (2 mm) and stored in labeled polyethylene jars to avoid contamination. Plant leaves were washed with distilled water and oven-dried at 70 oC for 48 h, ground in Wiley-Mill and stored in labeled polyethylene jars for chemical analysis. The groundwater samples from both sites were collected in cleaned and rinsed plastic bottles, filtered through Whatman No. 40 filter paper and stored in a freezer.

Oven-dried leaf samples weighing 0.5 g were transferred into a flask, treated with 10 mL of concentrated HNO_3 and left to digest overnight (Walsh and Beaton, 1977). After adding 4 mL of $HClO_4$, the flask was heated gently until the plant material digested. Upon cooling, contents were filtered through Whatman No. 40 filter paper and made to desired volume with distilled water.

Table 1. Pre-sowing chemical properties of soils and groundwater at the two experimental sites

Properties	Units	Range	Mean±St.Dev.	
	Site 1 (Silty clay loam, saline-sodic soil)			Irrigation Water-1
$pH_{(1:5)}$	-	8.17-8.85	8.64±0.26	8.20
EC_e	dS m^{-1}	4.23-9.45	5.55±1.56	5.02
Na	mmol (+) L^{-1}	32.6-64.2	39.5±9.81	27.65
Ca+Mg	mmol (+) L^{-1}	14.0-35.8	20.6±6.76	16.90
K	mmol (+) L^{-1}	0.23-0.59	0.36±0.13	0.07
SAR	-	10.4-15.2	12.4±1.43	9.51
	Site 2 (Clay loam, saline soil)			Irrigation Water-2
$pH_{(1:5)}$	-	7.62-8.06	7.85±0.16	8.10
EC_e	dS m^{-1}	3.20-5.00	4.24±0.58	2.40
Na	mmol (+) L^{-1}	11.5-22.3	15.6±3.73	13.50
Ca+Mg,	mmol (+) L^{-1}	18.8-33.0	27.2±5.20	9.50
K	mmol (+) L^{-1}	0.13-0.23	0.15±0.04	0.07
SAR	-	3.38-7.00	4.22±1.19	6.19

2.3. Analyses of soil, water and plant samples

Soil texture was determined using hydrometric method (Bouyoucos, 1962; Gee and Bauder, 1986). Saturated soil paste was prepared adding distilled water to 250 g soil in a plastic beaker while stirring with a spatula. Saturated soil paste was kept overnight to allow salt dissolution and equilibration (Richards, 1954), then transferred to the suction funnel with filter paper in place and vacuumed. The extract was collected in labeled polyethylene bottles for analysis. The pH of soil suspension with soil:water ratio of 1:5 and water samples was determined using the 105 Ion analyzer pH meter (McLean, 1982; Thomas, 1996). Electrical conductivity (EC) was measured using a digital EC meter, Wiss. Techn. Werkstatten (WTW) D12 Weilheim (Rhoades, 1982).

Soil saturation extracts, plant and water samples were analyzed for Na and K concentrations using a Perken-Elmer flame photometer model No.2380.

The concentrations of Na and K were calculated in mmol (+) L^{-1} (Richards, 1954). For determination of Ca and Mg, 3 mL of soil saturation extract, water or plant samples was taken into a 15 mL, wide mouthed porcelain crucible and 1 mL of NH_4CI plus NH_4OH and few drops Eriochrome Black-T were added. The sample was titrated against 0.01 N EDTA until the color was changed from wine red to blue or green (Richards, 1954). Using values of Na and Ca+Mg concentrations [mmol (+) L^{-1}] in soil saturation extracts and water samples, the SAR of the soils and water was calculated using the formula (Richards, 1954):

$$SAR = \frac{[Na]}{\sqrt{\frac{[Ca+Mg]}{2}}}$$

Data were subjected to an analysis of variance using the statistical package of MSTATC program (Steel and Torrie, 1980). We used sites and K rates as factors and treatment means were compared using Duncan's multiple range test at the 5% level of probability.

3. Results and Discussion

A summary of analysis of variance showing the F-ratios for wheat grain and dry matter yield, chemical composition of leaf tissue and post-harvest soil saturated extracts is given in Table 2.

3.1. Initial (pre-cultivation) chemical properties of soil and water

Chemical analyses of soil and water samples collected before sowing showed marked differences between the properties of the two sites (Table 1). Site 1 had higher pH1:5, ECe, and SAR than Site 2. Site 1 also had higher K level [0.23 to 0.59 mmol (+) L^{-1}] in soil saturation extracts than Site 2 [0.13 to 0.23 mmol (+) L^{-1}]. The ground water at Site 1 with relatively elevated salinity and sodicity might be responsible for the higher EC_e, Na, K and SAR for the site.

3.2. Wheat response to K fertilizer

The addition of K significantly increased grain and dry matter yield of wheat at both sites (Table 2). The two sites produced significantly (p<0.01) different dry matter yields but showed non-significant difference in grain yields. The soil and K interaction had marked effect on dry matter yield. The increases in grain yield observed at both sites with the given rates of K were similar (14 and 30%) but the increases (35 and 54%) in dry matter yield were higher in clay loam (Site 2) than the 7 and 29% increases observed in the silty clay loam soil (Site 1) [Table 3]. The poor crop yield of sodic soils is often associated with their low infiltration rates and restricted aeration because of high exchangeable Na (Jayawardane and Chan, 1994). Hence, the lower ECe , [Na] and ECiw in Site 2 than Site 1 explains the better wheat growth and dry matter yields in Site 2.

Potassium deficiency in plants reduced the growth rate (Mengel and Kirkby, 2001) but increased supplies of K make up for 6% of the plant dry matter (Leigh and Jones, 1984). In this study, the increased leaf tissue [K] induced by the added K was positively correlated with grain and dry matter yields of wheat at both sites [Figure1 (a) and (b)]. The screening processes of salt tolerance of crops, as suggested in Munns (2002) might be due to the concept of two-way growth response to salinity. The growth reduction in the first phase is due to salts in rooting media creating osmotic stress. The second phase growth reduction involves salt accumulation in leaves resulting in poor crop yields. The application of K in the present study improved wheat yield which might be due to increased salt tolerance as determined by the mechanism of salt exclusion associated with selectivity of K uptake by roots and preferential loading of K rather than Na in xylem (Jeschke, 1984; Munns, 2002). Previous studies confirmed the biochemical role of K in plant nutrition and osmoregulation in enhancing tolerance and mitigating the adverse effects of high salt concentrations in soils, thereby increasing crop yields (Garg and Gupta, 1998; Schachtman and Liu, 1999; Sherif *et al.*, 1998).

Various studies showed reductions in wheat yields with increasing salinity of irrigation waters. Sharma and Rao (1998) reported 4.2 to 22.2% yield reduction in wheat with increasing salinities from 6 to 18.8 dS m^{-1} of irrigation water. In our case, however, saline irrigation produced no significant change in yield which could be associated with the application of K and higher electrolyte concentrations (EC) of irrigation water which minimized the adverse effect of Na.

Table 2. Summary analysis of analysis of variance showing F-ratios for wheat grain and dry matter yield, chemical composition of leaf tissue and post-harvest soil saturated extracts of silty clay loam saline-sodic (Site 1) and clay loam saline (Site 2) soils

Source of variation	Wheat yield		Leaf tissue				Post-harvest soil saturation extract					
	Variables Analyzed											
	Grain	Dry matter	K	Na	Ca+Mg	K:Na	EC_e	K	Na	Ca+Mg	SAR	Na:K
	F-ratio											
K	14.3**	38.7***	11.7**	50.0***	0.66^{NS}	47.8***	2.4^{NS}	46.3***	7.62*	0.45^{NS}	5.84*	7.66*
Soil	1.11^{NS}	94.2*	158.3**	27.0*	4.0^{NS}	35.8*	56.4*	86.5*	62.1*	77.5*	19.2*	0.69^{NS}

*, **, ***= Significant at p<0.05, 0.01 and 0.001, respectively and NS= Not-significant

3.3. Chemical composition of wheat leaf tissue

The application of K significantly affected the leaf tissue [K] and [Na] and K:Na (Table 2) but the two soils behaved differently. The soil x K interaction had significant effect on [Na] and [K] and non-significant on [Ca+Mg] and K:Na ratio.

Consistent decreases in leaf tissue [Na] and increases in [K] with addition of 50 and 100 kg K ha^{-1} at both the sites were observed (Table 3). With addition of K, leaf tissues [Na] decreased by 14.5 and 38.3% at Site 1, and 37.2 and 63.8% at Site 2; the increased leaf tissue [K] showed positive correlation with grain yield of wheat at Site 1 (R^2 = 0.73) and Site 2 (R^2 = 0.80) as shown in Figure 1(a). The dry matter yield also showed positive correlation (R^2 = 0.92 and 0.71 for Site 1 and Site 2) with tissue K [Figure1(b)]. The uptake of K by wheat reduced Na uptake resulting in significant (p<0.01) increase in K: Na ratio of leaf tissues which might have enhanced grain yield by lowering Na toxicity. The relationship between grain yield with K:Na was better in silty clay loam soil (R^2 = 0.73) than clay loam soil [(R^2 = 0.49, Figure 2(a)]. The increase in leaf K:Na ratio was significantly correlated with dry matter yield at Site 1 (R^2 = 0.91) and Site 2 (R^2 = 0.62) as shown in Figure 2(b).

Table 3. Wheat grain and dry matter yields, composition of leaf tissue and post-harvest soils as affected by K application to silty clay loam saline-sodic (Site 1) and clay loam saline (Site 2) soils

Treatments	Wheat yield		Leaf tissue composition				Post-harvest soil composition						
K	Grain	Dry matter	K	Na	Ca+Mg	K:Na	$pH_{(1:5)}$	EC_e	K	Na	Ca+Mg	SAR	Na:K
kg ha^{-1}	--------Mg ha^{-1}---------		---------------mmol kg^{-1}------------					dS m^{-1}	---------mmol (+) L^{-1}sat.ext -----				
Site 1 (silty clay loam saline-sodic soil)													
0	2.00	9.10 d	420.3 c	54.5 bc	1433	7.79	7.81	4.60 b	0.20	21.7	24.5	6.16	108.2
50	2.28	9.77 d	527.2 b	46.6 cd	1533	11.4	7.88	5.58 a	0.28	29.8	24.7	8.50	105.7
100	2.60	11.7 c	668.4 a	33.6 e	1633	19.9	7.86	5.45 ab	0.34	30.6	24.8	8.67	90.0
Site 2 (clay loam saline soil)													
0	2.13	9.80 d	428.6 c	89.7 a	1500	4.78	7.99	1.84 c	0.07	10.3	6.17	5.91	147.9
50	2.42	13.2 b	474.3 bc	62.6 b	1533	7.62	7.88	1.63 c	0.11	11.1	5.00	7.06	99.7
100	2.62	15.1 a	499.1 bc	36.1 de	1767	14.2	7.90	1.69 c	0.18	11.9	6.67	6.62	67.0
Soils	---Averaged across (n=9) K levels---												
Site 1	2.29 b	10.2 b	538.5 a	44.9 b	1533 b	13.0 a	7.85	5.21 a	0.27 a	27.4 a	24.7 a	7.78 a	101.3
Site 2	2.39 a	12.7 a	467.3 b	62.8 a	1600 a	8.88 b	7.92	1.72 b	0.12 b	11.1 b	5.94 b	6.31 b	105.5
K (kg ha^{-1})	--Averaged across (n=6) soils--												
0	2.07 c	9.45 c	424.3 c	72.1 a	1467	6.29 c	7.90	3.22	0.14 c	16.0 b	15.4	6.04 b	128.0 a
50	2.35 b	11.5 b	500.7 b	54.6 b	1533	9.49 b	7.88	3.61	0.20 b	20.5 a	14.8	7.45 a	102.7 ab
100	2.61 a	13.4 a	583.8 a	34.8 c	1700	17.1 a	7.88	3.57	0.26 a	21.3 a	15.8	7.65 a	79.5 b

↑Means followed by similar letters in a column are non-significant at $p<0.05$

Since the total Na accumulated [concentration x DM yield, data not shown] also decreased with addition of K, the decrease in [Na] in the wheat leaf tissue could not be related to the dilution effect commonly associated with yield increases (Jarrell and Beverly, 1981).

The chemical composition of soil saturation extracts (Table 3) may also help to explain the variation in the crop yield. The soil at Site 2 had much lower [K] in saturation extracts [0.07 to 0.18 mmol (+) L^{-1}] than the soil of Site 1 [0.20 to 0.34 mmol (+) L^{-1}]. Such lower [K] might be a growth limiting factor at Site 2, but not at Site 1. This observation is in agreement with those of Bernstein *et al*. (1975) that plant growth is promoted more if the most limiting factor is relieved. With the addition of K_2SO_4 , the soil was able to replenish the K required and the plant uptake was adequate at Site 2 and hence the better crop growth. In the present study, the [K] in saturated soil extracts was positively correlated with tissue [K] (R^2 = 0.74, Site 1 and R^2 = 0.59, Site 2) as shown in Figure 3. Kemmler (1983) reported that wheat and other cereal crops frequently require about the same amount of K as N but the need for K might exceed that of N in some crop growth instances. The total K uptake is also influenced by soil available K level, amount of applied K fertilizer, soil fertility level, soil type and crop varieties. This leads to the conclusion that Site 2 being clay loam has stronger affinity for K adsorption (Khattak *et al*., 2002) and as such the addition of K fertilizers was more beneficial.

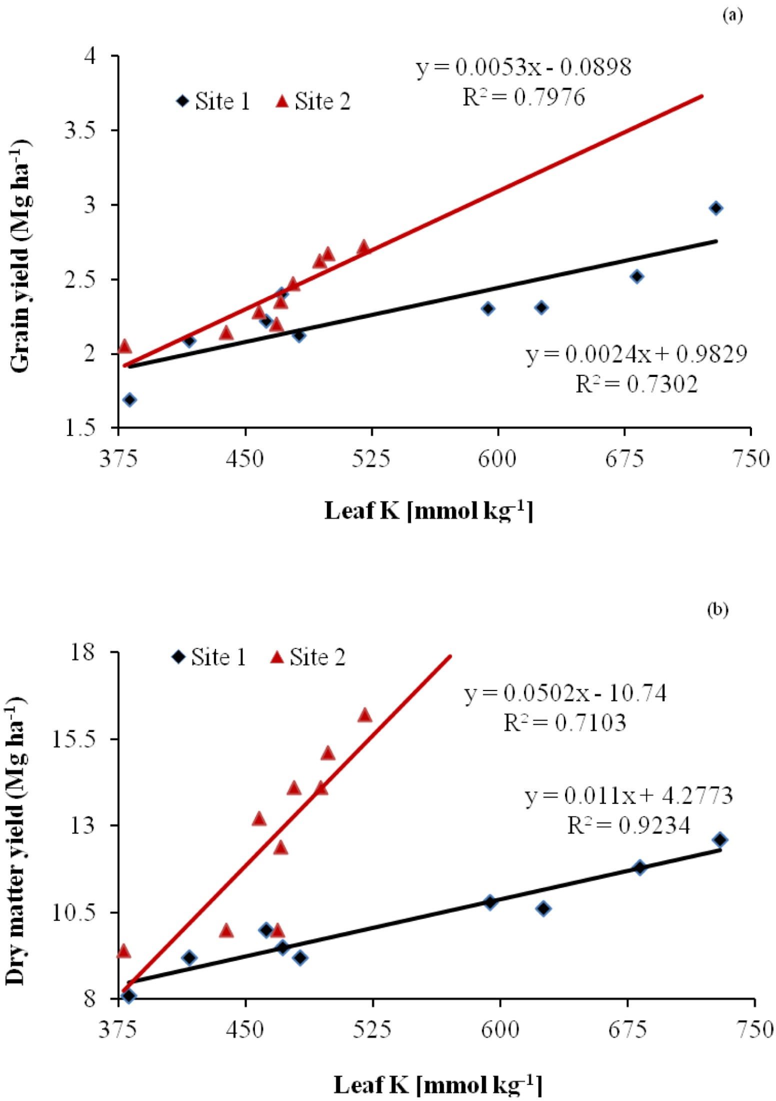

Figure 1. Regression of grain (a) and dry matter (b) yields of wheat versus leaf [K] (mmol kg^{-1}) in silty clay loam saline-sodic (Site 1) and clay loam saline soil (Site 2).

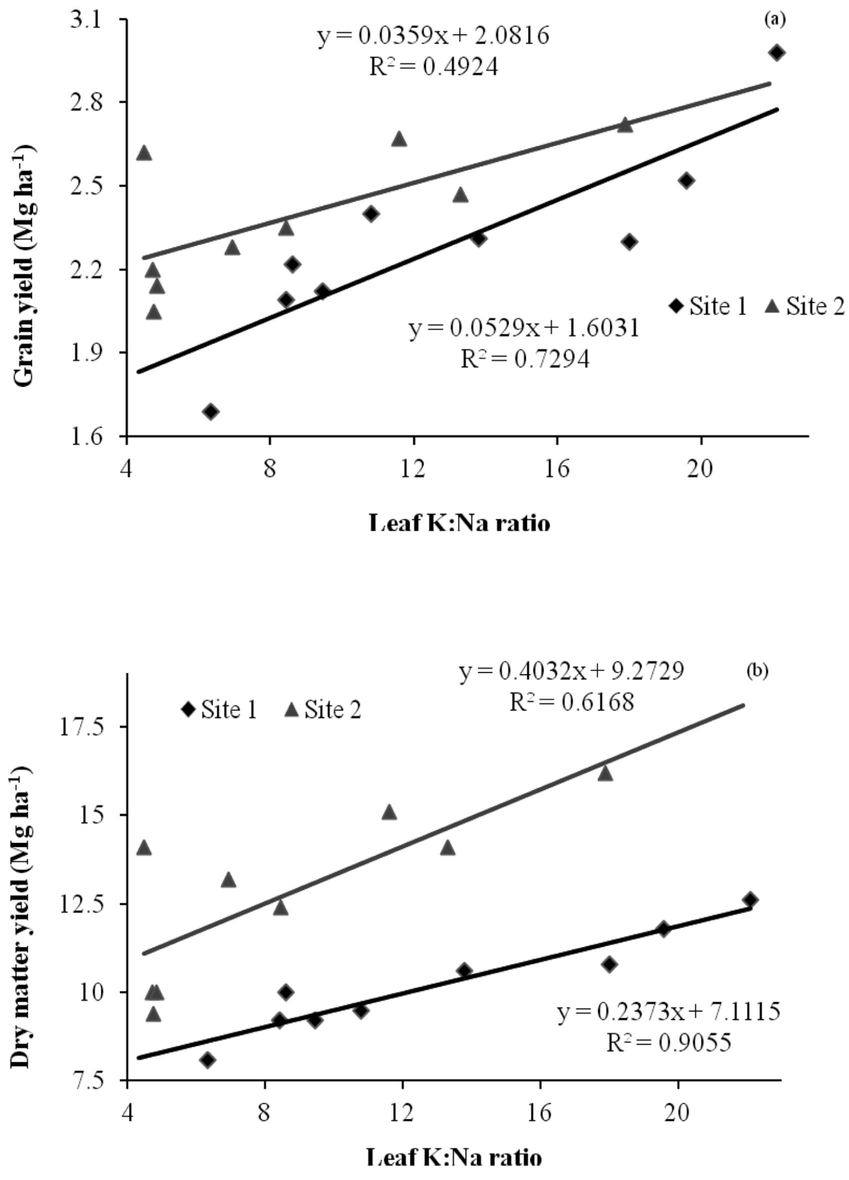

Figure 2. Regression of grain (a) and dry matter (b) yields of wheat versus leaf K:Na ratio in silty clay loam saline-sodic soil (Site 1) and clay loam saline soil (Site 2).

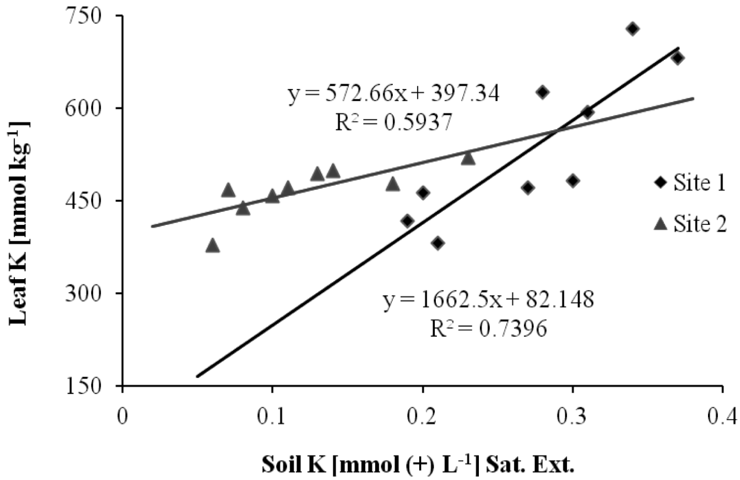

Figure 3. Relationship between soil saturation extract [K] and wheat leaf [K] in silty clay loam saline-sodic soil (Site 1) and clay loam saline soil (Site 2)

Although [Ca+Mg] was little affected, the uptake of both cations tended to increase with K addition in both soils, and might have improved shoot growth due to reductions in Na:Ca ratio as suggested in Grieve and Fugiyama (1987). Similarly, Kinraide (1999) reported that wheat tissue [Na] was reduced by Ca and K in the root zone and tissue [K] was enhanced by Ca and Na.

Various other studies have shown the positive trends of plants selectivity for K over Na and the increases in yields with increasing [K] due to increased K:Na ratios. For example, Chhipa and Lal (1995) reported that K:Na ratio > 6.67 in grain and > 2.50 in straw indicated the tolerance of wheat to sodicity. Similarly, Salam et al. (1999) concluded that inter-varietal variation in salt tolerance in wheat was controlled by genes and that the K:Na ratio of the youngest leaf could be used to screen for salt tolerance. Also, Na exclusion from wheat roots correlated well with salt tolerance of plants in the saline-sodic soils (Munns and James 2003). Therefore, the better grain and dry matter yields of wheat under the saline and saline-sodic soil conditions in the present study could be associated with higher K:Na ratios.

3.4. Post harvest soil solution concentrations

The addition of K did not significantly affect the post harvest soil pH(1:5), ECe and [Ca+Mg], however, [K] and [Na] tended to increase in soil saturation extracts of both sites (Table 3). A comparison of soil chemical composition of both site and with the initial (pre-sowing) composition revealed that the ECe and concentrations of all the cations were lower in the saline soil of Site 2 after harvesting than Site 1, which explains the relatively higher yield at Site 2.

The [K] in soil saturation extracts of Site 1 increased more than that of Site 2. Moreover, the groundwater used for irrigation had higher K concentrations at Site 1 than Site 2 which might have profound effect on K accumulation, hence the Na:K ratios in soil at Site 2 showed much better correlation ($R^2 = 0.75$) than the soil at Site 1 ($R^2 = 0.23$) (Table 2) with [K] in saturated extracts. The higher K concentration in soil ensured K availability and supported relatively equivalent grain yield at Site 1.

As compared to control, the SAR values increased significantly with the addition of K_2SO_4 in the silty clay loam and non-significantly in the clay loam soil. The [Na] in saturated extracts increased substantially in the silty clay loam and did not change in the clay loam which explains the observed variation in SAR. However, SAR values decreased substantially (5.91-8.61) with cropping as compared to pre-sowing values (10.4-14.2) (Table 1). The [Ca+Mg] did not change with addition of K but was higher in silty clay loam and lower in clay loam than pre-sowing values (Table 1).

The chemical analysis of post-harvest soil showed some positive changes when compared with the initial (pre-sowing) soil analysis. The addition of K tended to increase [K] and [Na] in soil saturation extracts but overall [Na], Na:K ratios and SAR decreased when compared to initial values. The increases in [Na] caused by addition of K_2SO_4 could be associated with displacement of Na by K into solution (Richards 1954; Levy and Feigenbaum 1996) and formation of soluble complexes which pulled Na into solution as soluble $Na_2SO_4^0$ and $NaSO_4^-$ (Spark, 1995).

In soil saturation extracts where the Na:K ratio was less than 4:1, the measured ESP and SAR were considerably lower than usually observed in high Na soils (Robbins, 1984). For soils in the present study, the Na:K ratios in soil saturation extracts were lower than the reported ratio (Robbins, 1984) even after K addition. According to Qadir *et al*. (2005), during the process of phyto-remediation of salt affected soils, the roots of crops increased the dissolution of calcite resulting to enhanced levels of Ca in soil solution to replace Na from the cation exchange complex.

The irrigation water used at Site 1 had high EC and SAR than that of Site 2 (Table 1). The higher salt concentrations in irrigation water of Site 1 added more salts to the soil. However, the lower concentrations of most of the cations in post-harvest soil might be due to leaching promoted by the silty clay loam texture of soils and higher electrolyte levels in irrigation waters at Site 1. The relatively higher average rainfall during the months of January - March (Soil Survey of Pakistan, 2007a) might also have contributed to leaching of most cations. Abbott *et al.* (1996) reported that use of saline water for irrigation increased soil salinity. However, it was possible to improve soil salinity and crop production by means of irrigation with saline water at certain growth stages (Ferdous *et al*. 1997). Continuous irrigation with such waters might reduce sodicity hazard through the replacement of the Na with K (Levy and Torrento, 1995).

The present study suggested that K_2SO_4 addition could promote crop yield under saline and saline-sodic conditions. Under such soil conditions, closure of stomata and inhibited photosynthetic activity due to lower K nutritional status induces the formation of toxic oxygen radicals (Cakmak 2005) and as such a higher K supply can counteract this effect under saline conditions (Abogadallah *et al*., 2010). Addition of K can mitigate the adverse effect of Na induced by saline and saline-sodic waters and thereby improve crop growth (Ali *et al*., 1999). However, focus must not be only on lowering of Na accumulation in shoot tissue as a measure of mitigation of salt stress as suggested in Shabala and Cuin (2008) but rather on K homeostasis maintaining a high K:Na ratio (Rubio *et al*., 2010) by preventing K losses by Na and/or Na-induced Ca deficiency.

The amelioration of saline-sodic soils due to improved K utilization with press mud application decreased the adverse effect of [Na] on plant (Muhammad and Khattak, 2009). Salt tolerant wheat lines showed higher K:Na ratios in leaf tissues which promoted crop yields in saline and saline-sodic soils (Hussain and Khattak, 2005). In the present study, a high K:Na ratio in leaf tissues was indicative of reduced uptake of Na from soil solution and/or increased uptake of K, thus minimizing its adverse effects. While these studies suggested the positive effects of K fertilization on soils and plants, more detailed studies are needed to explore the effects of associated anions such as SO_4, NO_3 and PO_4 on minimizing the adverse effect of Na and Cl in saline-sodic soils irrigated with saline water.

4. Conclusions

The yields of wheat significantly increased with the application of K fertilizer. The better yield and growth were paralleled by increased K:Na ratio at both sites, which also indicates an improvement in salt tolerance of the crop. The application of K_2SO_4 could promote crop yield and mitigate the adverse effect of Na and would thus be an effective approach to enhanced crop production in saline and saline-sodic soils.

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