Arch. Biol. Sci., Belgrade, 62 (4), 1053-1061, 2010 DOI:10.2298/ABS1004053A

ALLOMETRY AND YIELD COMPONENTS OF MAIZE (*ZEA MAYS* L.) HYBRIDS TO VARIOUS POTASSIUM LEVELS UNDER SALINE CONDITIONS

M. AKRAM[1*], M. Y. ASHRAF[2], RASHID AHMAD[3], M. RAFIQ[3], I. AHMAD[5] and JAVED IQBAL[4]

[1*] *Pulses Research Institute AARI,* Faisalabad, Pakistan
[2] *Nuclear Institute for Agriculture and Biology (NIAB), Jhang Road,* Faisalabad, Pakistan
[3] *Department of Crop Physiology, University of Agriculture,* Faisalabad, 38040 Pakistan
[4] *Oil seed Research Institute AARI, Jhang Road,* Faisalabad, Pakistan

Abstract - A field experiment was conducted to study the response of two maize hybrids to external K application under saline field conditions (ECe 5.71-8.91 dS m^{-1}). The data showed that there was an increase in the different growth and yield components with the increase in the external K. The increase was more pronounced when K was applied at the rate of 175 kg ha^{-1} with respect to control treatment. The enhanced growth and yield of these hybrids under saline conditions might be due to the response of K application, resulting in reduced Na uptake. The results indicated that the hybrids Pioneer 32B33 perform better than Dekalb 979 and economical yield can be obtained when potassium was applied at the rate of 125 kg ha^{-1}.

Key words: Potassium, salt tolerance, maize, growth, yield

UDC 633.15:631.527.5:581.1

INTRODUCTION

Salinity is a major environmental factor and is a constraint to food, feed and industrial raw material production because it limits crop yields and restricts the use of land previously uncultivated. In many arid and semi-arid regions, good soils are scarce with their overall productivity declining because of soil degradation and lack of proper soil and water management practices. Most salt-affected lands are found in the arid, semi-arid and coastal regions of sub-humid areas and are low in crop production (IAEA, 1995).

Salinity has three potential effects on plants: lowering of the water potential, specific ion toxicity (sodium and chloride) and interference in the uptake of essential nutrients (Flowers and Flowers, 2005). The adverse effects of salinity on plant growth and yield are of a multifarious nature, i.e. they may be due to reduced cell expansion and leaf area (Ashraf, 1998) or to a reduced supply of photosynthates to the growing tissues (Munns, 1993). The deleterious effects of salinity on plant growth are associated with the low osmotic potential of soil solution, thereby causing water stress, nutritional imbalance and specific ion toxicity or a combination of these factors (Marschner, 1995). There are different approaches to improving salinity tolerance in plants, i.e. the cultivation of salt tolerant plants, chemical methods and nutrient management in salt affected soils because plants need essential mineral nutrients to grow and develop. Nutrient management is a vital component of the scientific package of agriculture technology. However, the use of potassium is very much lower than recommended levels. The acquisition of K^+ is concerned due to physiological similarities between Na^+ and K^+ (Noaman, 2004). The capacity of plants to counteract salinity stress will strongly depend on the status of their K^+ nutrition. Potassium is essential to all plants and in most terrestrial plants K^+ is the major cationic inorganic nutrient and it also enhances several enzyme functions. Potassium acts to balance the charge in the cytoplasm of the cell, where K^+ is the dominant counter ion for the large excess of negative charge on proteins and nucleic acids (Yang et al., 2004). Potassium contributes more than Na^+, Cl^- and glycinebetaine in osmotic adjustment under saline conditions and activates the crucial enzymatic reactions such as formation of pyruvate. It is also a substantial contributor to osmotic pressure of the vacuole and thereby maintains cell turgor (Ashraf and Sarwar, 2002).

Maize is commonly classified as a moderately salt sensitive crop and considered as salt sensitive of cereal with yield reduction due to salinity that varies from 10% at an ECe of 1.7 dS m^{-1} to 50% at ECe 7 dS m^{-1} (Mass and Hoffman, 1997). However, there exists some variation within the species/genotypes for Na^+ accumulation and for discrimination in favor of K^+ transport to the shoot (Gorham, 1990). Because of the sensitivity of this crop, improvement of salt tolerance would be of considerable value. Effective and accelerated improvement through potassium application would be required in order to assess the potential to produce superior salt-tolerant cultivars.

MATERIAL AND METHODS

The crop was sown during the autumn on August 4, 2007 at the Post Graduate Agricultural Research Station (PARS), Jhang Road, Faisalabad. The experiment was laid out in a randomized complete block design with split plot arrangements. There were three replicates for each treatment. Net plot size was 5 m x 3 m. Maize hybrids and potassium levels were randomized in main and sub-plots, respectively. The two maize hybrids (Pioneer 32B33, Dekalb 979) were sown in saline field conditions (ECe 5.71-8.91 dS m^{-1}) with a single row hand drill in rows 75 cm apart, while a plant-to-plant distance of 22.5 cm was maintained later on by thinning. There were four levels of potassium which were applied: K_0: Control (no application), K_1: 75 kg K_2O ha^{-1}, K_2: 125 kg K_2O ha^{-1}, K_3: 175 kg K_2O ha^{-1}. Nitrogen and phosphorus were applied at 225 kg ha^{-1} and 125 kg ha^{-1}, respectively. Phosphorus and potassium were applied at sowing time. Nitrogen, phosphorus and potassium were used in the form of ammonium nitrate, single super phosphate (SSP) and sulphate of potash (SOP). Irrigation was applied as and when required. Hoeing was carried out 25 days and 35 days after sowing to control weeds. Granules of carbofuran were applied at 20 kg ha^{-1} on the stem tops to control maize stem borer 35 days after sowing. All other agronomic practices were kept uniform for all the treatments. Following observations were recorded:

Plant height at maturity: Five plants were harvested at random from each plot from ground level. Their height was measured by measuring tape at maturity and then average height was calculated.

Leaf area index: The leaf area of a 10 g subsample of green leaf lamina was measured on a leaf area meter (ΔT Area meter MK2) and on the basis of the fresh weight of the leaves of four plants per plot converted into per square meter. Leaf area index (LAI) was calculated as the ratio of leaf area to land area as suggested by Watson (1952).

$$\text{LAI} = \frac{\text{Leaf area}}{\text{Land area}}$$

Crop growth rate: Dry matter (DM) accumulation was determined at fortnight intervals by selecting five plants randomly from each subplot. The sampling was started 30 days after sowing (DAS) and terminated at the harvest of the crop. Soon after each harvest the samples were weighed to determine fresh weight. Each plant sample was chaffed, thoroughly mixed and then sun dried. Afterwards the samples were placed in oven at 70°C $\pm$ 5°C to dry the plant material to their constant dry weight. The dry weight per m^2 was calculated and used to estimate crop growth rate as proposed by Hunt (1978).

$$\text{CGR} = \frac{W_2 - W1}{t_2 - t_1}$$

CGR = Crop growth rate

W_2 = dry weight per unit land area (g m^{-2}) at second harvest

W_1 = dry weight per unit land area (g m^{-2}) at first harvest

t_2 = time corresponding to second harvest

t_1 = time corresponding to first harvest

Net assimilation rate: The net assimilation rate (NAR) was estimated using the formula of Hunt (1978).

$$NAR = \frac{TDM}{LAD}$$

TDM = Total dry matter, LAD = Leaf area duration

$LAD = (LAI_1 + LAI_2) \times (t_2 - t_1)/2$

LAI_1 = leaf area index at t_1 LAI_2 = leaf area index at t_2

t_1 = time corresponding to first harvest t_2 = time corresponding to second harvest

Cob length: The length of ten cobs was taken from each plot with the help of scale and then the average was taken. It was expressed in centimeter (cm).

Number of grains per cob: Ten cobs were selected at random from each plot. Grains were shelled by hand and the number of grains was counted. Then the average of these ten cobs' grains was calculated.

Number of grain rows per cob: Ten cobs were selected randomly from each plot and the number of grain rows in each cob was carefully counted and averaged.

100-grain weight: 100-grain were taken at random from the grain lot of each sub-plot and weighed by means of electric balance.

Biological yield: After harvesting the crop from each plot the whole material was sun dried. The total weight of cobs and stalks per plot was determined with the help of an electric balance and then converted on a hectare basis.

Grain yield: All the cobs in each plot were shelled, sun dried and weighed. Then this weight of grains per plot was converted into kilograms per hectare.

Harvest index: The harvest index (HI) was calculated as the ratio of grain yield to biological yield and expressed in percentage. Harvest index was calculated by using the following formula:

$$HI = \frac{\text{Grain yield}}{\text{Biological yield}} \times 100$$

Economical analysis

The experimental data were analysed by using methodology described in CIMMYT (1988). For an economic point of view, the cost of production of the maize was calculated in both the experiments during 2007 by applying potash under saline conditions. Net income and BCR (benefit cost ratio) was computed to examine the most profitable treatment.

STATISTICAL ANALYSIS

Data regarding various growth and yield parameters were collected using standard procedures and were analyzed statistically by using Fisher's analysis of variance technique. Three replicates for each treatment were maintained in each experiment. The treatments' means were compared using the least significant difference test at 5% probability level (Steel et al. 1997).

RESULTS

Leaf area index (LAI) is an indicator of the size of the assimilatory system of a crop. Periodic data on LAI are presented in Fig. 1a and Fig. 1b, respectively. The leaf area index progressively increased up to 60 days after sowing and then declined to the final harvest

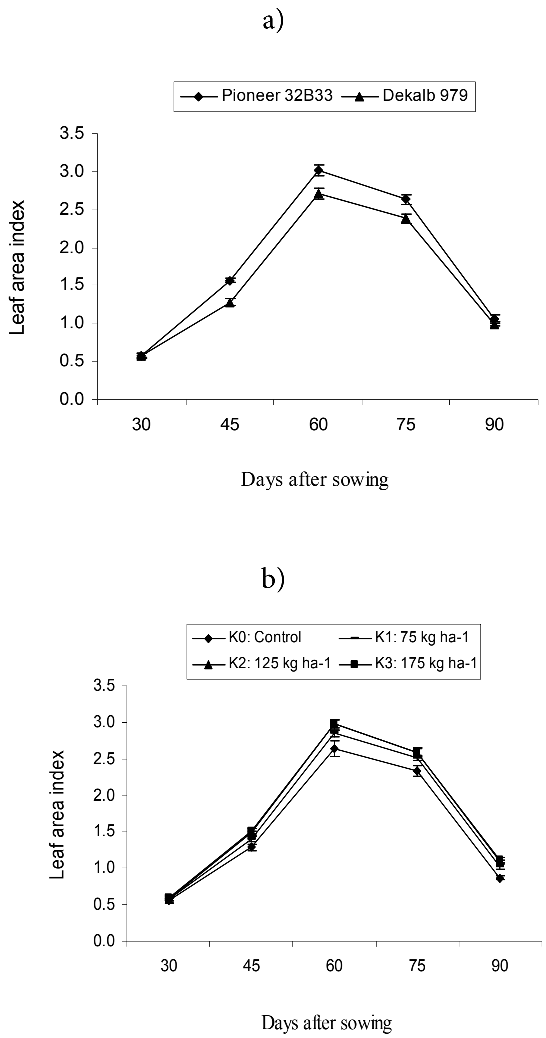

Fig. 1. (a, b) Leaf area index as affected by different potassium levels ± SE

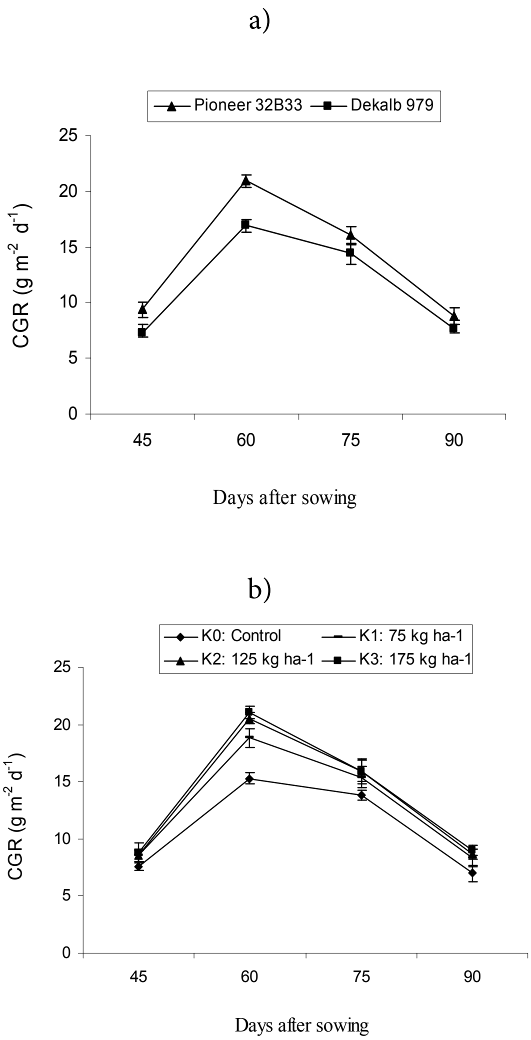

Fig. 2. (a, b) Crop growth rate (CGR) as affected by different potassium levels ± SE

(90 days after sowing). The LAI was very low in the beginning (30 days after sowing) but varied significantly in the hybrids and among the different potassium levels. It increased progressively with the advancement of the growth period and after reaching the maximum, it started to decline up to final harvest of the crop. The potassium levels significantly affected the LAI. Namely, non-significant differences between K_2 (125 kg K_2O ha^{-1}) and K_3 (175 kg K_2O ha^{-1}) throughout the season suggest that application of potassium above 125 kg K_2O ha^{-1} had no effect on LAI. Interaction between the hybrids and potassium levels was non-significant throughout the season of the crop. Regression analysis between LAI and grain yield attributes indicates a highly significant relationship (Fig. 3b).

Crop growth rate (CGR) expresses the rate of dry matter accumulation. Data pertaining to CGR recorded at fortnightly intervals in both hybrids and under different potassium levels are depicted in Fig. 2a and Fig. 2b. CGR increased, due to an in-

Table 1. Physico-chemical properties of soil of the experimental site

Description	Value
Soil texture	Clay loam
Saturation percentage	33.7
Electrical conductivity (dS m^{-1})	5.71-8.91
Soil pH	7.72 - 7.90
Ca + Mg (meq/L)	9.21 - 14.37
Sodium (meq/L)	16.7 - 29.28
Total nitrogen (%)	0.030
Available potassium (meq/L)	1.55 - 2.01
Phosphorus (ppm)	5.7
Carbonate (meq/L)	Nil
Bicarbonate (meq/L)	3.33 - 3.66
Chloride (meq/L)	9.4
Sodium absorption ratio (SAR)	11.01 - 19.03

crease in dry matter accumulation, in a linear fashion with a progressive increase in growth period in both the hybrids and under different potassium levels. With time, it reached its maximum value showing significant variation among different treatments (60 days after sowing) and thereafter declined up to harvest of crop. Interaction between the maize hybrids and different potassium levels was non-significant. Regression analysis indicates that there was a highly significant relationship between LAI and CGR (Fig. 3a).

Data (Table 2) indicates that there was a non-significant difference in the hybrids with respect to net assimilation rate (NAR). Potassium treatment significantly enhanced the net assimilation rate. Maximum NAR was observed when potassium was at the rate of 175 kg K_2O ha^{-1} which was at a par with all other treatments except the control treatment, where the crop was grown without the application of potassium. The interaction between maize hybrids and potassium levels was non-significant.

Data presented in Table 2 show that a significant difference in the maize hybrids with respect to plant height. Individual comparison of nitrogen treatment means indicates that a maximum plant height was recorded in treatment K_3 (125 kg K_2O ha^{-1}) which was at a par with K_2 (175 kg K_2O ha^{-1}), and the minimum was recorded in the control. Plant height was 18.56% higher when potassium was applied at the rate of 125 kg K_2O ha^{-1} compared to the control.

The cob length also determines the productivity of a maize crop which ultimately contributes to the final grain yield. Significant differences were found in the maize hybrids with respect to cob length. Potassium treatment means indicate that cob length increased with the application of potassium (Table 2).

There was a non-significant difference between the maize hybrids by number of grains per cob. The potassium means indicate that the number of grains per cob significantly increased with the application of potassium up to the optimal level (125 kg ha^{-1}), but there was no significant increase in this variable above the optimal level under saline conditions (Table 2). The interaction between maize hybrids and different potassium levels was non-significant. Regression analysis clearly shows that there was a highly significant relationship between the number of grain per cob and grain yield attributes (Fig. 4).

Data on the number of grain rows per cob as affected by different potassium treatment under saline conditions are presented in Table 2. A non-significant difference was found in the maize hybrids with respect to the number of grain rows per cob. The application of potassium significantly improved the number of grain rows per cob. However, the interaction between the hybrids and potassium levels was non-significant.

The 100-grain weight differed significantly in the maize hybrids (Table 2). Comparison among potassium levels indicate that 100-grain weight increased with the application of potassium. The maximum grain weight was recorded in the K_3 (175 kg K_2O ha^{-1}) treatment, which was at a par with K_2

a)

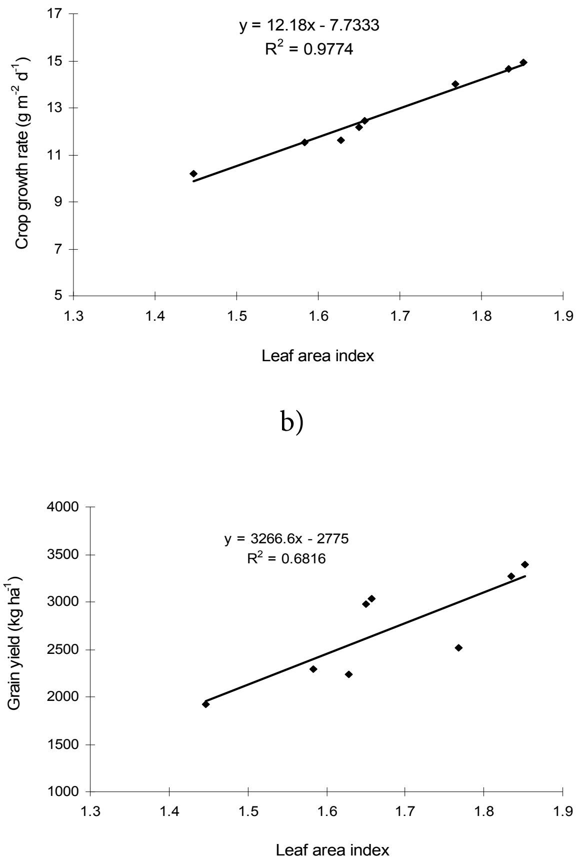

Fig. 3. Regression between (a) leaf area index and crop growth rate (b) leaf area index and grain yield in maize hybrids

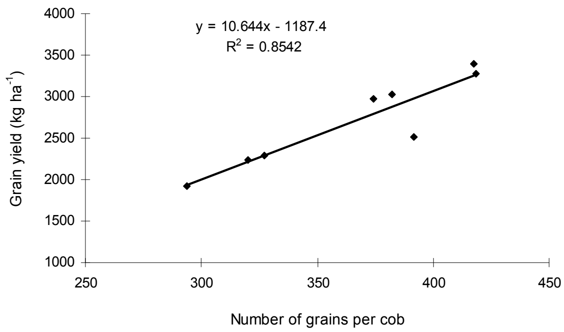

Fig. 4. Regression between number of grains per cob and grain yield in maize hybrids

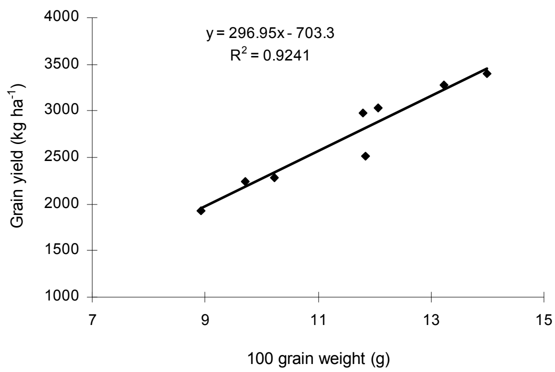

Fig. 5. Regression between 100-grain weight and grain yield in maize hybrids

(125 kg K_2O ha^{-1}), and the minimum, was found in the control (no application). The interaction between the hybrids and potassium levels was non-significant. Regression analysis indicates that there was a highly significant relationship between 100-grain weight and grain yield parameters (Fig. 5).

Biological yield is the overall expression of biological forces embodied in a production system which are affected by the different treatments applied in the present study. Biological yield differed significantly in the maize hybrids (Table 2). Data pertaining to the biological yield of maize as affected by different potassium levels indicate a significant effect of potassium application on the parameter under discussion. The interaction between hybrids and potassium was non-significant.

The final grain yield is a function of the cumulative effects of various yield components developed under a particular set of environmental conditions. Pioneer 32B33 produced significantly more grain yield (2855 kg ha^{-1}) than Dekalb979 (2554 kg ha^{-1}). All the potassium treatments differed significantly from each other with respect to grain yield (Table 2). The interaction between the maize hybrids and potassium levels was non-significant.

The harvest index is the ratio of economic yield to biological yield. It is an important parameter indicating the photosynthetic efficiency of a crop in the transformation of the photosynthates into the economic yield. The harvest index in the maize hybrids differed non-significantly (Table 2). The comparison among different potassium treatments shows significant variations among the different potassium levels. The interaction between the maize hybrids and potassium levels was non-significant.

DISCUSSION

It is quite clear that salinity affects crop production and agricultural sustainability in many regions of the world mainly by reducing the value and productivity of the affected land. Results of the present studies clearly indicated that potassium application under saline conditions significantly improved the growth of the crop. The leaf area index (LAI) indicates the size of the assimilatory system of the crop. The decline in leaf area index 60 days after sowing might be the result of leaf senescence experienced by the older leaves due to the low availability of sunlight (Fig 1a, b). It was improved by the application of potassium. Leaf area index reduction also occurred due to a decreased leaf expansion rate (leaf size) and this reduction in leaf expansion rate might be the result of reduced water and turgor potential. Masood et al., found that the application of potassium under saline conditions increased the yield and yield components of maize cultivars. Similarly, Davis et al. (1996) reported that the application of potassium has a promotive effect on growth, development and grain yield in maize. An adequate supply of potassium confers salinity tolerance in plants.

Crop growth rate (CGR) expresses the rate of dry matter accumulation. Salinity stress reduced the assimilatory system that resulted in a reduced photosynthesis and hence a low fresh or dry biomass accumulation. It is a common adverse effect of salinity stress on crop plants in the reduction of fresh and dry biomass production. The application of potassium significantly improved the periodic CGR under saline conditions (Fig. 2b). The findings of our study are also in line with the findings of Loreto et al. (2003), who reported that the decline in growth observed in many plants subjected to salinity stress is often associated with a decrease in their photosynthetic capacity. Improvement in the crop growth might be the result of maintenance of photosynthetic activity owing to potassium application.

Earlier, Mengel and Kirkby (2001) reported that potassium is essential for many physiological processes such as photosynthesis, translocation of photosynthates into sink, activation of enzymes and the reducing of excess uptake of sodium in saline soils. Moreover, in the present experiment the effect of the application of potassium was more pronounced in improving the yield components of the maize crop under saline conditions (Table 2). Aslam et al. (1998) described the application of potassium to rice in salt-affected soils using salt-tolerant and salt-sensitive cultivars, and reported that paddy and straw yield and 1000-grain weight increased as a result of potassium application. The maintenance of high cytoplasmic levels of potassium is therefore essential for plant survival in saline habitats. An adequate supply of potassium to plants growing in saline stress environments is believed to have an important role in inducing tolerance (Chow et al. 1990). In the present study, application of potassium at the optimal level (125 kg ha^{-1}) significantly improved the growth and yield (Table 2). This may be due to turgor pressure and maintenance of water and nutrient uptake because potassium plays an important role in osmoregulation. Similar findings were earlier found by Davis (1994) and Finck (1998), who reported that potassium plays an important role in the osmotic adjustment of plants under stress and yield may increase significantly as a result of potassium application. Application of potassium at a higher level increased the plant growth as well as yield components. Moreover, the beneficial effect of an increased level of potassium application on grain yield was due to the maintenance of water relation and mineral nutrition.

Table 2. Effect of different potassium levels on net assimilation rate, plant height, and yield and yield components of maize hybrids under saline conditions

Treatments	Net assimilation rate (g m-2 d-1)	Plant height (cm)	Cob length (cm)	Number of grains cob-1	Number of grain rows cob-1	100-grain weight (g)	Biological yield (Kg ha-1)	Grain yield (Kg ha-1)	Harvest index (%)
					Mean				
Maize hybrids (H)									
Pioneer 32B33	7.44	140.83 a	13.10 a	387.00	12.66	12.19 a	12115 a	2855 a	23.43
Dekalb 979	7.01	125.50 b	11.30 b	344.00	12.00	10.75 b	10827 b	2554 b	23.41
LSD at 5%	NS	6.41	0.53	NS	NS	0.86	554.12	82.82	NS
Potassium levels (K) (kg ha^{-1})									
K_0 : Control	6.74 b	118.50 c	10.63 c	307.00 c	10.33 c	9.32 c	9952 d	2081 d	20.88 b
K_1 : 75	7.36 a	128.70 b	11.82 b	359.30 b	11.67 b	11.03 b	11050 c	2400 c	21.72 b
K_2 : 125	7.41a	140.00 a	13.04 a	396.30 a	13.33 a	12.52 a	11980 b	3123 b	26.12 a
K_3 : 175	7.40 a	145.50 a	13.33 a	399.80 a	14.00 a	13.03 a	12900 a	3214 a	24.99 a
LSD at 5%	0.19	6.77	0.56	15.31	1.11	0.91	584.70	87.40	1.30
Interaction (H x K)	NS	NS	NS	NS	NS	NS	NS	NS	NS

Means sharing the same letters in a column do not differ significantly at p 0.05
*, ** = Significant at P ≤ 0.05 and P ≤ 0.01 levels respectively
NS = Non significant

Table 3. Effect of potassium applications on net income and benefit-cost ratio (BCR)

Treatments	Total expenditure (Rs. ha^{-1})	Gross income (Rs. ha^{-1})	Net income (Rs. ha^{-1})	BCR
		Potassium applications		
K_0 : Control	27176	33816	6640	1.24
K_1 : 75 kg K_2O ha^{-1}	30826	39000	8174	1.27
K_2: 125 kg K_2O ha^{-1}	33226	50732	17506	1.53
K_3: 175 kg K_2O ha^{-1}	35626	52227	16601	1.47

Economic analysis

Economic analysis indicates that different levels of potassium application resulted in different net income (Rs. ha^{-1}) as indicated in Table 3. Application of potassium at 125 kg K_2O ha^{-1} resulted in the highest net income of Rs. 17506 during the year 2007. The highest benefit cost ratio

(BCR) of 1.53 was recorded in the K_2 (125 kg K_2O ha^{-1}) treatment.

Acknowledgment - The authors are very grateful to the Higher Education Commission Pakistan for the financial assistance for conducting the experiments.

REFERENCES

Ashraf, M. Y., and *G. Sarwar* (2002). Salt tolerance potential in some members of *Brassicaceae*. Physiological studies on water relations and mineral contents. In *Prospects for saline Agriculture*. Ahmad R, Malik KA (Eds.) Kluwer Academic Publishers, Netherlands, pp. 237-245.

Ashraf, M. Y. (1998). Photosynthetic efficiency of wheat under water stress conditions. *Pakistan journal of Scientific and Industrial Research* **41**, 156-163.

Aslam, M., Ahmad, M., Qureshi, R. H., and *S. Nawaz* (1998). Composition of different methods of potassium application to rice (*Oryza sativa* L.) in a salt affected soil. *Pakistan Journal of Soil Science* **14,** 17-20.

Chow, W. S., Ball, M. C., and *J. M. Anderson* (1990). Growth and photosynthetic responses of spanich to salinity: implications of K nutrition for salt tolerance. *Australian Journal of Plant Physiology* **17**, 563-578.

CIMMYT, (1988). An Economic Training Handbook. Economic Programme. CIMMYT, Mexico.

Davis, J. G. (1994). Managing plants nutrients for optimum water use efficiency and water conservation. *Advances in Agronomy* **53**, 85-120.

Davis, J. G., Walker, M. E., Parker, M. B., and *B. Mullinix* (1996). Long term phosphorus and potassium application to corn on coastal plain soils. *Journal of Production in Agriculture* **9,** 88-94.

Finck, A. (1998). Integrated nutrient management: an overview of principles, problems and possibilities. *Annal of Arid Zone* **37**, 1-24.

Flowers, T. J., and *S. A. Flowers* (2005). Why does salinity pose such a difficult problem for plant breeders? *Agriculture water management* **78**, 15-24.

Gorham, L. (1990). Salt tolerance in triticieae. Ion discrimination in rye and Triticales. *Journal of Experimental Botany* **41**, 609-614.

Hunt, R. (1978). Plant growth analysis, pp. 26-38. Edward Arnold, Olondon, UK.

IAEA, (1995). Management strategies to utilize salt affected soils. IAEA-TECDOC-814, Soil fertility, Irrigation and crop production section, Joint FAO/IAEA Division of nuclear techniques in food and agriculture, Vienna, Australia.

Loreto, F., Centritto, M., and *K. Chartzoulakis* (2003). Photosynthetic limitations in olive cultivars with different sensitivity to salt stress. *Plant Cell and Environment* **26**, 595-601.

Maas, E.V., and *G. J. Hoffman* (1997). Crop salt tolerance, current assessment. *Journal of Irrigation and Drainage Division ASCE* **103**, 115-134.

Marschner, H. (1995). Mineral nutrition of higher plants. 2nd edn. London: Academic Press.

Maqsood, T., Akhtar, J., Farooq, M. R., Haq, M. A., and *Z. A. Saqib* (2008). Biochemical attributes of salt tolerant and salt sensitive maize cultivars to salinity and potassium nutrition. *Pakistan Journal of Agricultural Sciences* **45**, 1-5.

Mengel, K., and *E. A. Kirkby* (2001). Principles of plant nutrition. 5th ed. Kluwer Academic Publishers, Dordrecht, London.

Munns, R. (1993). Physiological processes limiting growth in saline soils: some dogmas and hypotheses. *Plant and Cell Environment* **16**, 15-24.

Noaman, M. N. (2004). Effect of potassium and nitrogen fertilizers on growth and biomass of some halophytes grown under high level of salinity. *Journal of Agronomy* **3**, 25-30.

Steel, R. G. D., Torrie, J. H., and *D. A. Deekey* (1997). Principles and procedures of statistics: A Biometrical Approach. 3rd ed. McGraw Hill Book Co. Inc. New York. 400-428.

Watson, D. J. (1952). The physiological basis of variation in yield. *Advances in Agronomy* **4**, 101-145.

Yang, X. E., Liu, J. X., Wang, W. M., Ye, Z. Q., and *A. C. Luo* (2004). Potassium internal use efficiency relative to growth vigour potassium distribution and carbohydrates allocation in rice genotypes. *Journal of Plant Nutrition* **27**, 837-852.