Pak. J. Bot., 41(6): 2965-2974, 2009.

BIOMASS AND NUTRIENT UPTAKE BY RICE AND WHEAT: A THREE-WAY INTERACTION OF POTASSIUM, AMMONIUM AND SOIL TYPE

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Abstract

Potassium (K)-ammonium (NH_4^+) interaction for biomass production and K uptake determined by nutrient solution may be modified by soil type due to variable clay content and constituent clay minerals. Rice and wheat response to various combinations of K and NH_4^+ was investigated in three soils in a replicated three factors factorial pot experiment. Combinations of K 0, 300 and 600 mg kg^{-1} and NH_4^+ 0, 115, and 230 mg kg^{-1} soil were applied in Kotly, Gujranwala, and Lyallpur soils. Rice tillers per plant and dry matter, and K content in various plant parts increased under the main effects (K, NH_4^+) but several two-way interactions were also significant. Biomass production was highest at the highest NH_4^+ application level (230 mg kg^{-1}) for the silty clay Kotly soil and lowest for the sandy loam Lyallpur soil. It suggests the role of clay content in temporarily retaining cations and avoiding suppression of biomass in the presence of NH_4^+. Maximum K content in rice plant was with 300 mg K and 115 mg NH_4^+ kg^{-1} soil. Interaction of K and NH_4^+ on K uptake was significant. The highest K content in plant tissue was at the application level of 300 mg K kg^{-1} and 0 NH_4^+. Plant tissue K decreased with each addition of NH_4^+ at 300 mg K kg^{-1} but at the highest K application of 600 mg kg^{-1} soil no reduction in plant tissue K occurred. The study suggests that response of rice and wheat in terms of biomass production and K accumulation vary with K and NH_4^+ levels as well as K and NH_4^+ interaction changed with the soil type.

Introduction

Potassium (K) and ammonium (NH_4^+) availability and uptake by crops is controlled by several biotic and abiotic factors e.g. chemical speciation of inorganic nitrogen in soil influencing uptake of K^+ and its distribution within the plant. Ammonium has been shown to reduce the primary influx of K^+ from soil solution and accumulation in plant tissue (Santa-Maria *et al*., 2000). Ammonium induced reduction in the primary influx of K^+ can be alleviated by increasing soil solution K^+ concentration (Kronsucker *et al*., 2001). Further, soil solution K^+ is controlled by characteristics and dominance of soil minerals as abiotic factors. Quantitative distribution of K-containing weatherable minerals such as biotite and K-feldspar vary with soil type (Akhtar & Dixon, 1989, 2009). Potassium supply in the Indus plain soils is generally adequate (Awan *et al*., 1998). But most Pakistani soils are deficient in N, and N fertilization is extensive at least in the irrigated plain. An adequate amount of available K is known to enhance N use efficiency by crops (Hagin *et al*., 1990).

Potassium deficiency increases the chances of NH_4^+ toxicity by causing a high internal concentration of ammonia. An increase in the availability of K through soil minerals or fertilizer application can improve N use efficiency. This interaction can be exploited to enhance N utilization. The interaction of K^+ with NH_4^+ is one of the most important phenomena observed in plant nutrition (Munson, 1970; Loue, 1978) but is rarely investigated in field conditions (Bartlett & Simpson, 1967). When availability of K^+ varies with mineral composition of the soil, its interaction may vary with soil type.

The soils which contain partially weathered mica, vermiculite, or high charge smectite as dominant clay minerals have low soil solution K^+. Whereas soils supplied with NH_4^+ fertilization enhance the K availability to plants by occupying the highly K-specific adsorptions sites in clay minerals (Kilic *et al*., 1999). Since clay minerals retain K^+ and NH_4^+ irreversibly by the same mechanism, one cation affects the fixation and plant availability of the other cation (Page *et al*., 1967; Chen & Mackenzie, 1992). The K-NH_4^+ interactions are complex, and addition of NH_4^+ as fertilizers might increase K availability in certain soils whereas in others the opposite can be true (Barbayiannis *et al*., 1996). Classical work by Bartlett & Simpson (1967) reported the response to sequence of K and NH_4^+ application. Potassium applied before NH_4^+ decreased the NH_4^+ fixation in all soils but when it was applied with NH_4^+ it increased the NH_4^+ fixation in some soils (Kilic *et al*., 1999). Application of NH_4^+ before the addition of K had almost no effect on the availability of K and equilibration of soil with NH_4^+. Ammonium is more capable of displacing K from the solid surfaces than K for NH_4^+ (Barbayiannis *et al*., 1996).

Several studies reported crop response to N and K application individually e.g. wheat (Hamid & Ahmad, 1995), sugarcane (Ashraf *et al*., 2008), brassica cultivar (Aziz *et al*., 2006), cotton (Kumbhar *et al*., 2008) and several others. Scanty information is available on the interactive effect of K and the forms of N for crop production and the nutrient uptake from soils containing different suite of clay minerals. The main objective was to determine K^+ and NH_4^+ interaction for rice and wheat biomass production and K uptake from soils differing in mineral composition.

Materials and Methods

Description of soils: The soils included in the study are developed in calcareous alluvium derived from variety of sedimentary rocks and represent range of clay content and mineralogical composition. These are: (i) Lyallpur, fine-silty, mixed, hyperthermic Ustic Haplocambid formed in the semi-arid part of the Old River terraces; (ii) Gujranwala, fine-loamy, mixed, hyperthermic Typic Haplustalf formed in the subhumid part of the Old River terraces; and (iii) Kotly, fine, smectitic, hyperthermic Entic Chromustert formed in subhumid part in basin channel infill position in the Sub-recent floodplain. The field observations and pedological work suggested that these soils with respect to degree of mineral weathering can be ordered as Kotly > Gujranwala > Lyallpur (Ahmad *et al*., 1977).

Mineralogical composition and plant available K indices for the soils under study were published previously (Akhtar & Dixon, 1993; Awan *et al*., 1998a, b; Akhtar & Dixon, 2009). The Kotly soil clay is composed of mostly smectite and kaolinite and has lower K-fixing capacity than that of Gujranwala soil (Awan *et al*., 1998b). The Gujranwala soil clay is composed of mica, smectite and kaolinite with a measurable amount of vermiculite and partially weathered mica (Akhtar & Dixon, 2009). The Lyallpur soil clay is composed of mica, kaolinite and smectite and has greater concentration of divalent cations in the clays and lesser charge density smectite compared to the Gujranwala. The Lyallpur soil maintains greater K activity in equilibrium solution but has lower buffering capacity than the Gujranwala. Characteristics of the soils relevant to K and NH_4^+ chemistry are given in Table 1.

Table 1. Selected properties of the soils controlling plant available K.

Soil/Horizon	pH†	EC_e‡	K-fixed¶	NH4-K#	sand	silt	clay	AR_e^K	ΔK_{iw}	PBC^K	Clay mineralogy††
		dS m^{-1}	mg kg^{-1}		------ % -------						
Kotly											
Ap (0-10 cm)	7.78	1.19	440	198	4	40	56	1.80	0.21	260	Smectite, kaolinite
BA (10-20 cm)	7.98	1.27	390	182	4	38	58	1.00	0.35	290	
Gujranwala											
Ap (0-11 cm)	8.01	1.45	540	125	23	57	17	1.91	0.91	30	mica, smectite, kaolinite, vermiculite
BA (11-20 cm)	8.01	1.50	550	130	26	55	18	1.18	1.26	83	
Lyallpur											
Ap (0-11 cm)	8.35	1.86	290	120	25	59	13	8.12	-0.12	41	mica, kaolinite, smectite
BA (11-22 cm)	8.45	1.98	280	100	28	62	14	2.80	0.10	48	

†, pH of soil water saturated paste

‡, EC_e electrical conductivity of saturated soil paste extract

¶, K retained against extraction with NH_4^+ when excess amount was applied, equilibrated by repeated wetting and drying, and extracted with neutral 1 N NH_4Oac

#, ambient level of plant available K estimated by extraction with 1 N NH_4OAc

††, dominant clay minerals estimated using X-ray diffraction and cation exchange properties.

AR_e^K, equilibrium activity ratio of potassium (Akhtar and Dixon, 1989).

ΔK_{iw}, potassium adsorbed on interlayer and wedge sites of clay layered silitcates

PBC^K, buffering capacity for change in K

Note the difference in Q/I parameters (AR_e^K, ΔK_{iw}, PBC^K) obtained between Kotly and Lyallpur. The Kotly soil had a high PBC^K which will keep AR_e^K at a low and fixed level and the content of high labile K^+ and will increase with increasing addition of K. In contrast, The Lyallpur soil with low PBC^K will have considerable variation of both the AR_e^K and labile K content. But, the Lyallpur soil also had high weatherable K bearing minerals which will keep high AR_e^K. The same process may be expected for NH_4^+ except its release from soil mineral.

Soil sampling and preparation: Bulk surface (0-20 cm) samples of Kotly, Gujranwala and Lyallpur soil series were collected from field sites representative of each soil series: (a) the Kotly soil, seven km from Gujranwala on Gujranwala-Sialkot road; (b) the Gujranwala soil, one km from Gujranwala on Gujranwala-Alipur Chatha road; and (c) the Lyallpur soil, seven km from Faisalabad on Faisalabad-Jhang road. The samples were air-dried and passed through a 6.4 mm screen. Five kg of each soil was filled in separate plastic pots of 30 cm height and 25 cm diameter.

Fertilizer application and test-crop sowing: Potassium 0, 300, and 600 mg kg^{-1} soil from K_2SO_4; and 0, 115, and 230 mg NH_4^+ kg^{-1} soil from $(NH_4)_2SO_4$ salts were applied to each soil in three replications. In addition, basal dose of 200 mg P kg^{-1}, 10 mg Zn kg^{-1} and 1 mg B kg^{-1} soil were applied to each pot using K_2HPO_4, $ZnSO_4$ and H_3BO_4, respectively. The salts were thoroughly mixed in individual pots and distilled water was applied to raise moisture level to saturation. Four 21-day old rice (*Oryza sativa* L., cv. Basmati-385) seedlings were transplanted in each pot, and raised using distilled-water irrigation in a greenhouse. Flag leaves of 30-day old rice plants and whole shoot of one plant at 55-day age were sampled from each pot. The remaining three plants per pot were grown for 70 days and number of tillers and biomass produced were recorded.

After harvesting rice, five wheat (*Triticum aestiuum* L. cv. Pak-8l) seeds were sown in the same pots. Wheat received only 0, 115 and 230 mg NH_4^+ kg^{-1} soil and a basal dose for 200 mg P kg^{-1} soil. After emergence, thinning was done to three wheat plants per pot. Number of tillers per plant, biomass, and grain yield were recorded. The wheat plants were grown to maturity using distilled water for irrigation in the greenhouse. Soil water during wheat growing season was maintained in the pots at slightly below the field capacity.

Analytical procedures: Rice and wheat plant tissue samples were separately analyzed for K by dry ash method. Potassium in dry ash was dissolved in 4 M HNO_3 and assayed by atomic absorption spectroscopy. Nitrogen was analyzed by Kjeldahl method (Jackson, 1958). Analysis of variance (ANOVA) was conducted using three factors factorial design including the main treatment effects (Soil type, K, and NH_4^+) and all possible interactions using Statistical Analysis System (SAS Inc., 2003). The treatment means were compared by Duncan's Multiple Range Test, and various interactions were plotted.

Results and Discussion

Ammonium (main effect and its interactions): Vegetative mass of rice averaged over the soil types and K level increased with application of up to the highest level of NH_4^+ (230 mg kg^{-1} soil), while wheat vegetative mass and grain yield increased with NH_4^+ application up to 115 mg kg^{-1} soil (Fig. 1). Obviously, NH_4^+ utilization by rice and/or tolerance to high NH_4^+ is better than other cereals (Sasakawa & Yamamoto, 1978).

Soil type changed the biomass response to NH_4^+ application eg., rice biomass in response to NH_4^+ application in the Kotly soil increased up to 230 mg kg^{-1} application, in the Gujranwala soil, the increase was relatively slow, and in the pots with Lyallpur soils actually a decrease in vegetative mass occurred (Fig. 2a). There was greater difference in wheat biomass and its grain production in response to NH_4^+ application in the Kotly and Lyallpur pots (Fig. 2b, c). Increase in wheat biomass and grain yield was up to 115 mg NH_4^+ kg^{-1}; and at 230 mg kg^{-1} there was no increase in both Kotly and Gujranwala soils, and in the Lyallpur soil a greater decrease occurred compared to that in rice (compare Fig. 2a and Fig. 2b). The Kotly soil has the highest clay content (<2 µm size soil fraction) dominated by smectite, hence, temporary retention of NH_4^+ and slow release to solution by the clay was possible. Greater biomass reduction at 230 mg NH_4^+ kg^{-1} in relatively coarse textured Lyallpur soil than fine textured Kotly soil suggests effect of clay content and composition in buffering NH_4^+ in soil solution (Table 1). Assuming 50 % soil porosity and no adsorption on clay (which is unlikely though), the 5 kg soil pot could contain maximum 25 mM NH_4^+ at saturation point and as high as 50 mM NH_4^+ at 50 % field capacity. Therefore, decrease in vegetative mass could be due to NH_4^+ toxicity (Kronzucker *et al*., 2001) caused limited K^+ uptake in the presence of high concentration of NH_4^+ (Szczerba *et al*., 2008). It is more likely to occur in the Lyallpur soil since it contains only 10 % clay. Therefore, it is possible that applied NH_4^+ remained in soil solution at a greater level in Lyallpur than in Kotly soil and caused injury to plant cells.

Not only the soil type - NH_4^+ level interaction, K - NH_4^+ application level interaction for vegetative growth and plant tissue K was also significant (Fig. 3). The study indicates that average rice vegetative mass increase in response to NH_4^+occurred only when optimum K application was done as with no application of K increase in vegetative mass did occur beyond 115 mg kg^{-1} (Fig. 3a). Plant tissue K increased with increased NH_4^+ level at ambient K level in soil-solution (as that controlled by soil minerals with no applied K) or when 600 mg K kg^{-1} soil was applied (Fig. 3b). However, the highest K content in plant tissue was observed at 300 mg K kg^{-1} soil and 0 NH_4^+ application levels, and it decreased with each application level ofNH_4^+. At the highest K application level (600 mg K kg^{-1} soil) reduction in plant tissue K had not occurred. Ammonium supply has been shown to reduce influx of K^+, and the inhibition of K influx can be removed by increasing the external K concentration (Santa-Maria *et al*., 2000; Kronzucker *et al*., 2003; Szczerba *et al*., 2006). Application of NH_4^+ increased the plant tissue N content and N uptake in 30-day leaves and 55-day shoots of the rice crop (data not presented). Soil type - NH_4^+ level interaction on 30-day leaves K and the plant tissue N content were statistically non-significant. The effect of applied NH_4^+ level on tissue K and N content of 55-day shoots of rice was dependent on soil type. Similarly K and N uptake as influenced by NH_4^+ level varied with soil type.

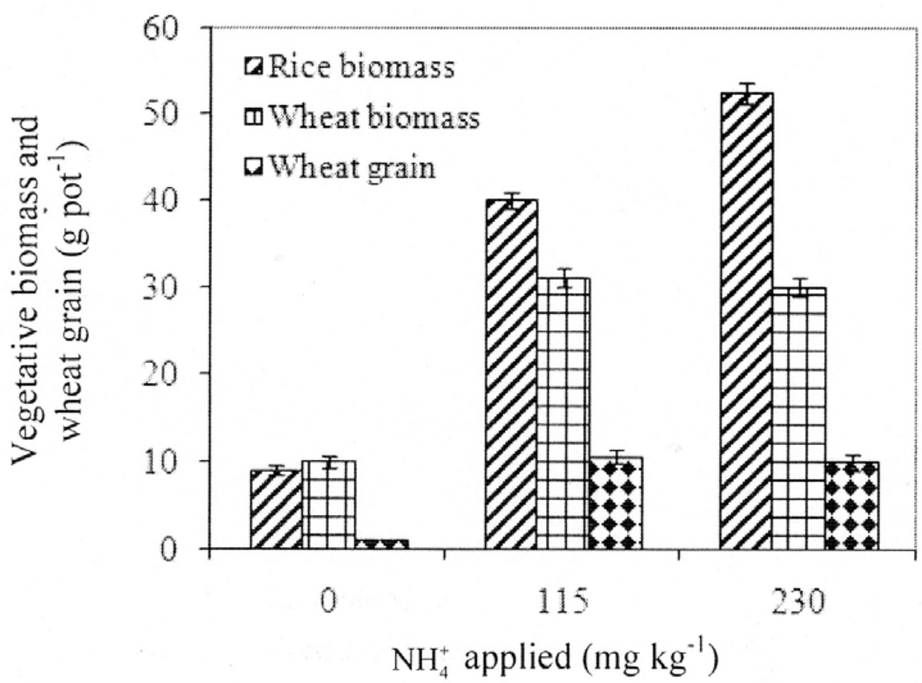

Fig. 1. Vegetative biomass of rice and wheat averaged under the main effect of NH_4^+ application level. Rice biomass increased up to 230 NH_4^+ (mg kg^{-1} soil) and wheat biomass and grain yield increased up to only 115 (mg kg^{-1} soil).

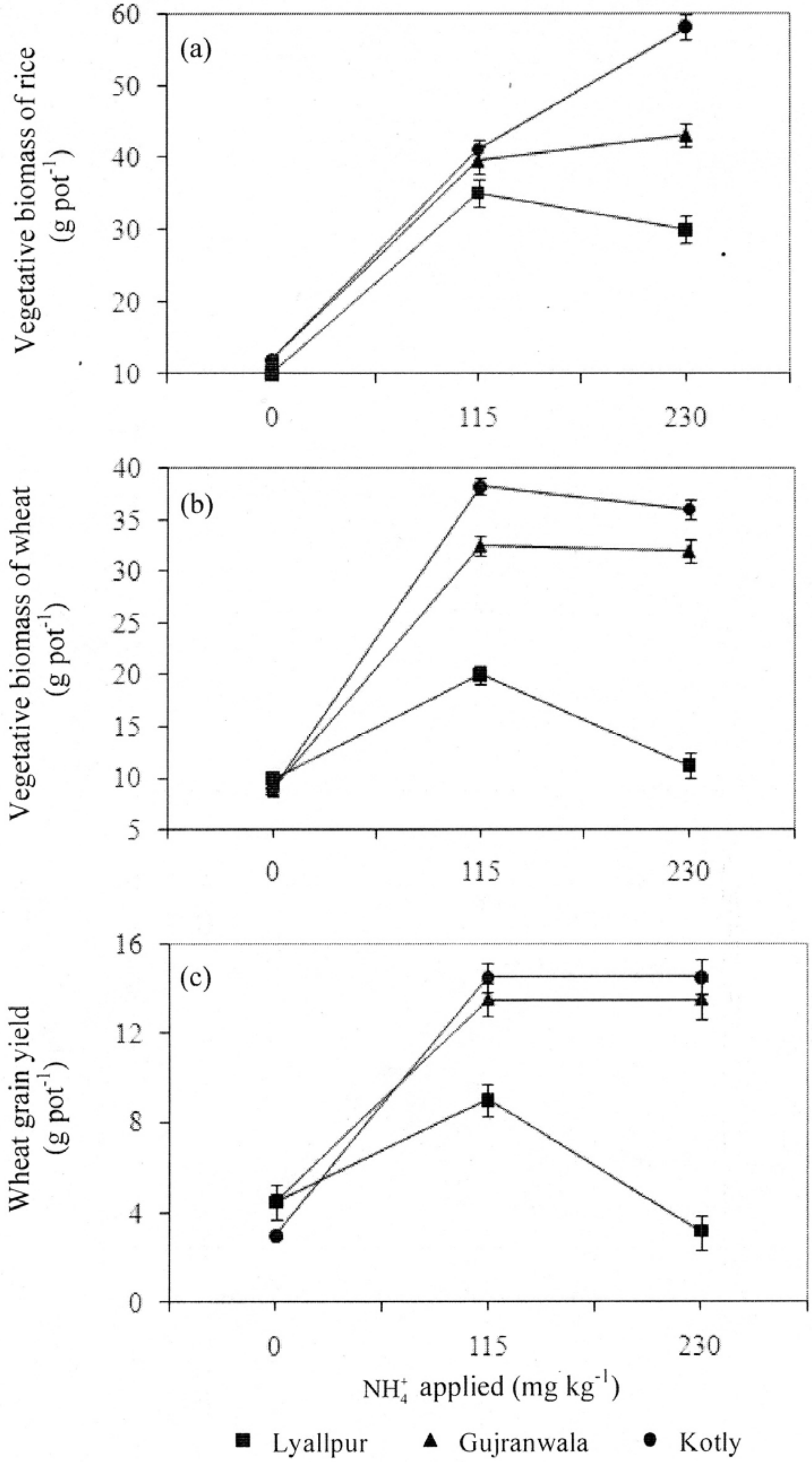

Fig. 2. Vegetative growth (Rice and wheat) and grain yield of wheat as affected by interaction between soil-type and applied NH_4^+ level: (a) vegetative rice biomass, (b) vegetative wheat biomass, and (c) wheat grain yield. Vegetative biomass increased with NH_4^+ application level of 230 mg kg^{-1} in silty clay Kotly soil, a reduced increase in the silty loam Gujranwala, and a decrease in the sand loam Lyallpur soil.

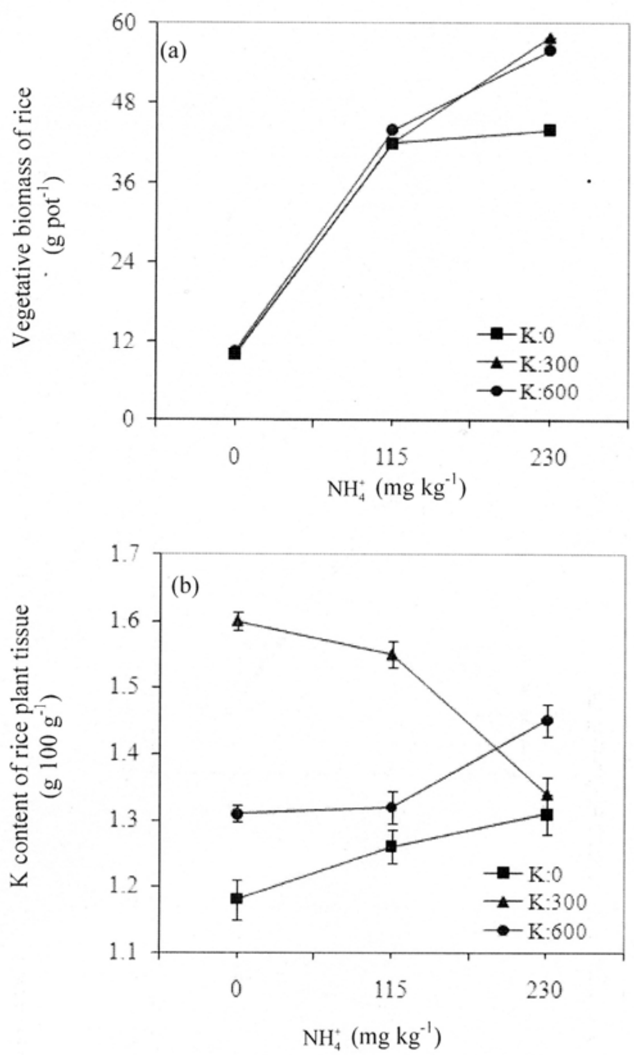

Fig. 3. Vegetative biomass and plant tissue K content as a result of interaction between applied K^+ and NH_4^+: (a) rice vegetative biomass; (b) rice plant tissue K. K-0, zero mg kg^{-1} K^+ application; K-300, 300 mg kg^{-1} K^+ application; K-600, 600 mg kg^{-1} K^+ application. The figure indicates rice vegetative biomass increase in response to NH_4^+ only when K^+ application was 300 mg kg^{-1}; and the highest plant tissue K when application of K^+ was 300 mg kg^{-1} and NH_4^+ was below 115 mg kg^{-1} soil.

Potassium (main effect and its interaction): Application of K resulted in significant increase in vegetative mass and number of tillers of rice and grain yield of wheat in these three soils. Rice and wheat biomass (averaged over the three soil types and NH_4^+ applied) increased up to 300 K mg kg^{-1} soil and additional K had no effect (data not presented). Potassium-soil interaction for biomass production of rice and wheat was non-significant probably due to very complex nature of K-availability from soil minerals. The treatments where no K was applied, biomass production was the highest in Lyallpur and the lowest in Gujranwala soil (data not presented). This phenomenon can probably be attributed to plant K requirement being met by direct weathering of mica in the presence of low K content in soil solution (Sparks & Huang, 1985). Lyallpur soil contains high content of K-containing un-weathered minerals (Akhtar & Dixon, 2009), and consequently it maintains high equilibrium activity of K^+ compared to other two soils (Table 1). Potassium application increased K content in 30-day leaves and 55-day shoots of rice (Fig. 4a). Potassium uptake by rice increased with K application up to 300 mg K kg^{-1} soil. An increase in K content due to K application in 30-day leaves, 55-day rice shoots and uptake by rice were dependent on soil type (data not presented).

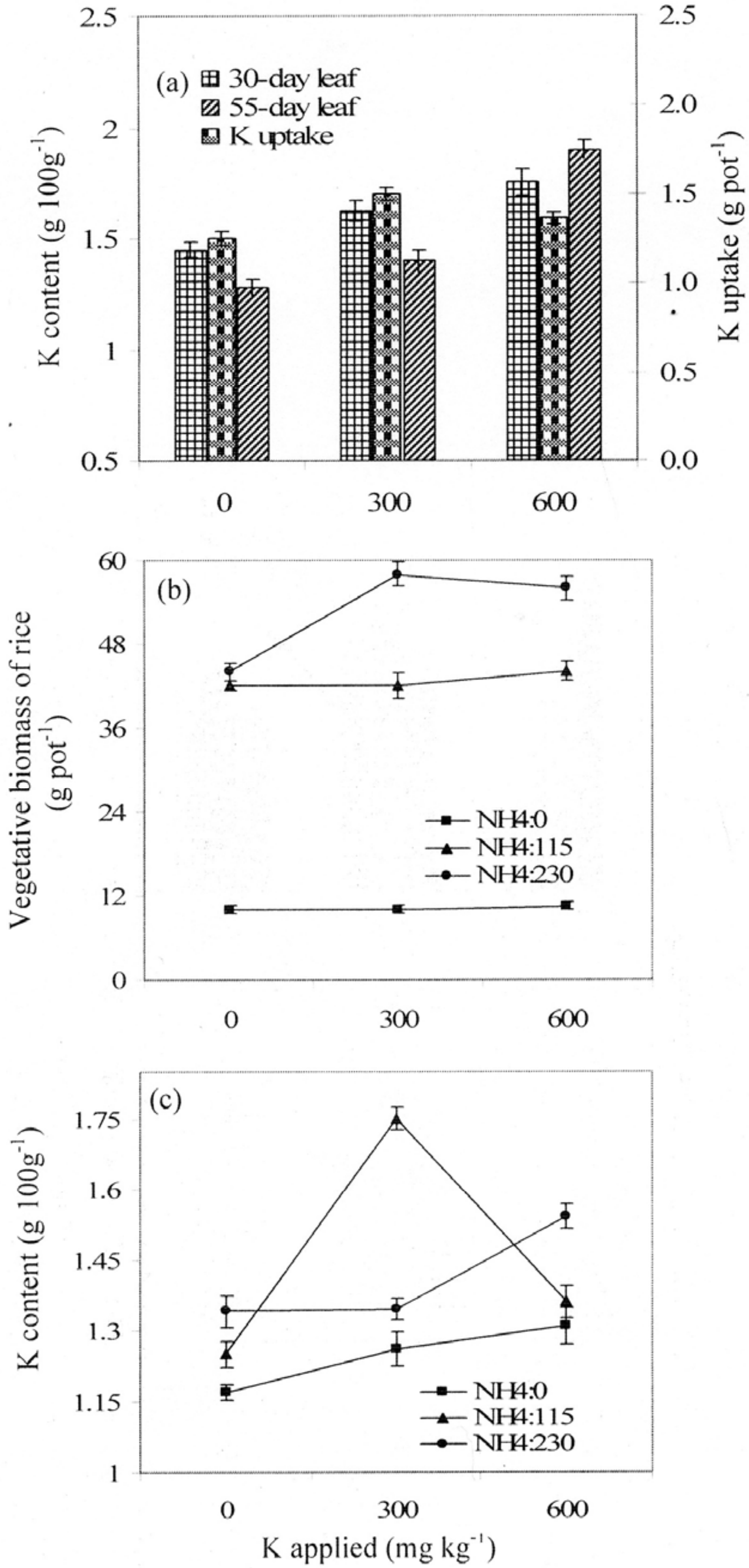

Fig. 4. (a), Plant tissue K in 30-day and 55-day rice leaf and the K uptake by rice under the main effect of applied K^+ level; (b), vegetative rice biomass at various levels of K^+ as affected by NH_4^+ application; and (c), rice K content at various levels of K^+ as affected by NH_4^+ application. NH4:0, zero mg NH_4^+ kg^{-1} soil; NH4:115, 115 mg NH_4^+ kg^{-1}; and NH4:230, 230 mg NH_4^+ kg^{-1}.

Effect of K level on biomass of rice (Fig. 4b) and number of tillers per wheat plant (data not presented) was modified by NH_4^+ level indicating significant NH_4^+-K interaction. Application of 230 mg NH_4^+ kg^{-1} soil was beneficial for rice biomass (averaged over three soils) when at least 300 mg K kg^{-1} soil was applied. Further increase in K application rate did not enhance biomass at any level of NH_4^+. An adequate supply of K increases biomass production by enhancing NH_4^+ utilization (Hagin *et al*., 1990). Also, uptake of K is dependent on the N level (Talibudin *et al*., 1976). Potassium uptake increased with increasing level of K when NH_4^+ level was at zero and at 230 mg NH_4^+ kg^{-1} (Fig. 4c); yet, in both the cases K uptake remained low apparently for different reasons (Kronzucker *et al*., 2003; Szczerba *et al*., 2006). Potassium increased with increase in K application when NH_4^+ was applied at 115 kg^{-1} soil up to 300 mg K kg^{-1} soil, and any further increase in K actually suppressed the K uptake. The best K uptake was at 115 mg NH_4^+ kg^{-1} soil and at 300 mg K kg^{-1} soil.

References

Ahmad, M., J. Ryan and R.C. Peath. 1977. Soil development as a function of time in the Punjab River Plains of Pakistan. *Soil Sci. Soc. Am. J*., 41: 1162-1186.

Akhtar, M.S. and J.B. Dixon. 1989. Mineralogy and potassium quantity/intensity relation in alluvial soils of Pakistan. *Sciences Géologiques, Mémoire (France)*, 85: 185-193.

Akhtar, M.S. and J.B. Dixon. 1993. Mineralogy and mineral proportion of surface soils from the Indus Plain of Pakistan. *Clay Res*., 12: 22-32.

Akhtar, M.S. and J.B. Dixon. 2009. Mineralogical characteristics and potassium quantity/intensity relation in three Indus River basin soils. *Asian J. Chem*., 21: 3427-3442.

Ashraf, M.Y., F. Hussain, J. Akhtar, A. Gul1, M. Ross and G. Ebert. 2008. Effect of different sources and rates of nitrogen and supra optimal level of potassium fertilization on growth, yield and nutrient uptake by sugarcane grown under saline conditions. *Pak. J. Bot*., 40: 1521-1531.

Awan, Z.I., M. Irshad and M.S. Akhtar. 1998a. Potassium release characteristics of sand and silt in relation to soil parent material and weathering stage. *Pak. J. Soil Sci*., 15: 94-106.

Awan, Z.I., M. Irshad and M.S. Akhtar. 1998b. Potassium fixation in relation to soil parent material and weathering stage. *Pak. J. Soil Sci*., 5: 106-115.

Aziz, T., Rahmatullah, M.A. Maqsood, M.A. Tahir, I. Ahmad and M.A. Cheema. 2006. Phosphorus utilization by six brassica cultivars (*Brassica juncea* L.) from tri-calcium phosphate; a relatively insoluble P compound. *Pak. J. Bot*., 38: 1529-1538.

Barbayiannis, N., V.P. Evangelou and V.C. Keramidas. 1996. Potassium-ammonium-calcium quantity/intensity studies in the binary and ternary modes in two soils of micaceous mineralogy of northern Greece. *Soil Sci*., 161: 716-724.

Bartlett, R.J. and T.J. Simpson. 1967. Interaction of ammonium and potassium in a potassium-fixing soil. *Soil Sci. Soc. Am. J*., 31: 219-222.

Chen, J.S. and A.F. Mackenzie. 1992. Fixed ammonium and potassium as affected by added nitrogen and potassium in three Quebec soils. Commun. *Soil Sci. Plant Anal*., 23: 1145-1159.

Hagin, J., S.R. Olsen and A. Shaviv. 1990. Review of interaction of ammonium-nitrate and potassium nutrition of crops. *J. Plant Nutr*., 13: 1211-1226.

Hamid, A. and M. Ahmad. 1995. Interaction of 15N-labelled ammonium nitrate, urea and ammonium sulphate with soil N during growth of wheat (*Triticum aestivum* L.) under field conditions. *Biol. Fert. Soils* (Germany), 20: 185-189.

Jackson, M.L. 1958. *Soil Chemical Analysis*. Prentic-Hall, New York. p. 183-204.

Kilic, K., M.R. Derici and K. Saltali. 1999. The ammonium fixation in great soil groups of Tokat Region and some factors affecting the fixation I. The affect of potassium on ammonium fixation. *Tr. J. Agric. Forest*., 23: 673-678.

Kronzucker, H.J., D.T. Britto, R.J. Davenport and M. Tester. 2001. Ammonium toxicity and the real cost of transport. *Trends Plant Sci*., 6: 335-337.

Kronzucker, H.J., M.W. Szczerba and D.T. Britto. 2003. Cytosolic potassium homeostasis revisited: ^{42}K-tracer analysis revealed set point variation in [K^+]. *Planta*, 217: 542-546.

Kumbhar, A.M., U.A. Buriro, S. Junnejo, F.C. Oad, G.H. Jamro, B.A. Kumbhar and S.A. Kumbhar. 2008. Impact of different nitrogen levels on cotton growth, yield and n-uptake planted in legume rotation. *Pak. J. Bot*., 40: 767-778.

Loue, A. 1978. The interaction of potassium with other growth factors particularly with other nutrients. p. 407-433. *Proc. 11th Cong. Intl. Potash Inst., Bern*.

Munson, R.D. 1970. N-K balance, an evaluation. Potash Review, Subject 16, 50th suit. *Intl. Potash Inst., Bern*.

Page, A.L., W.D. Burge, T.J. Ganje and M.J. Garber. 1967. Potassium and ammonium fixation by vermiculitic soils. Soil *Sci. Soc. Am. J*., 31: 337-341.

Santa-Maria, G.E., C.H. Danna and C. Czibener. 2000. High affinity-potassium transport in barley roots. Ammonium-sensitive and –insensitive pathways. *Plant Physol*., 1(123): 297-306.

SAS Institute Inc. 2003. SAS for Windows. Version 9.0. SAS Institute, Cary, NC.

Sasakawa, H. and Y. Yamamoto. 1978. Comparison of the uptake of nitrate and ammonium by rice seedling. Influence of light, temperature, oxygen concentration, exogenous soucrose, and metabolic inhibitors. *Plant Physiolgy*, 62: 665-669.

Sparks, D.L. and P.M. Huang. 1985. Physical chemistry of soil potassium. In: *Potassium in Agriculture*. (Eds.): R.D. Munson et al. ASA, Madison. pp. 201-276.

Szczerba, M.W., D.T. Britto and H.J. Kronzucker. 2006. Rapid, futile K^+ cycling and pool-size dynamics define low-affinity potassium transport in barley. *Plant Physiol*., 141: 1494-1507.

Szczerba, M. W., D. T. Britto, S. A. Ali, K. D. Balkos and H. J. Kronzucker. 2008. NH_4^+-stimulated and -inhibited components of K^+ transport in rice (*Oryza sativa* L.). *J. Expt. Bot*., 59: 3415-3423.

Talibudin, O., M.B. Page and J.D.D. Mitchell. 1976. The interaction of nitrogen and potassium nutrition on dry matter and nitrogen yields in the graminae: Pwewnniallye grass. *J. Sci. Food Agric*., 2: 999-1004.

(Received for publication 13 May 2009)