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Exploitation of potassium by various crop species from primary minerals in soils rich in micas

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Abstract We investigated the question of whether exchangeable K^+ is a reliable factor for K^+ availability to plants on representative arable soils (Aridisols) rich in K^+-bearing minerals. Five soils with different textures were collected from different locations in Pakistan and used for pot experiments. The soils were separated into sand, silt, and clay fractions and quartz sand was added to each fraction to bring it to 1 kg per kg whole soil, i.e., for each fraction the quartz sand replaced the weight of the two excluded fractions. On these soil fraction-quartz mixtures wheat, elephant grass, maize, and barley were cultivated in a rotational sequence. Growth on the sand mixture was very poor and except for the elephant grass all species showed severe K^+-deficiency symptoms. Growth on the mixture with silt and clay fractions was much better than on the sand fraction; there was no major difference in growth and K^+ supply to plants whether grown on silt or clay, although the clay fraction was rich and the silt fraction poor in exchangeable K^+. On both these fractions the plant-available K^+ supply was suboptimal and the plants showed deficiency symptoms except for the elephant grass. This plant species had a relatively low growth rate but it grew similarly on sand, silt, and clay and did not show any K^+ deficiency symptoms, with the K^+ concentration in the plant tops indicating a sufficient K^+ supply regardless of which soil fraction the plants were grown in. The reason for this finding is not yet understood and needs further investigation. It is concluded that on soils rich in mica, exchangeable K^+ alone is a poor indicator of K^+ availability to plants and that mica concentrations in the silt and clay fraction are of greater importance in supplying crops with K^+ than exchangeable K^+.

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Introduction

More than half the soils in the surveyed area of Pakistan are classified as Aridisols (Ahmad and Amin 1986). Crop responses of these soils to K^+ fertilizers are very irregular and sporadic. Until now the reason for this behaviour has not been clear. Some researchers found good crop responses to K^+ fertilizers when the soils were fairly high in exchangeable K^+ at around 200 mg K^+ kg^{-1} soil while 100 mg K^+ kg^{-1} was considered sufficient by others (Bhatti et al. 1983; Ahmad and Rahman 1984; Khan 1985; Gurmani et al. 1986). Other researchers concluded that the soils of Pakistan contain sufficient exchangeable K^+ (exchangeable with NH_4^+ acetate) and K^+-bearing minerals able to release enough K^+ to meet crop requirements (Sillanpaa 1982; Sadiq 1986; Malik et al. 1989). The question therefore arises of whether exchangeable K^+ is a reliable indicator of the soil K^+ available to crops in the Aridisols of Pakistan and whether K^+ directly released from primary K^+-bearing minerals can contribute to plant nutrition to any great extent.

In soils under a moderate climate, so-called non-exchangeable K^+ can be exploited by plants (Mengel 1985). The non-exchangeable K^+ available to crops is mainly interlayer K^+ in primary and secondary clay minerals, mainly in illite clay, which is micaceous in structure (Tributh 1987). K^+-bearing primary minerals are present to a substantial extent in the silt and also in the sand fraction of soils while interlayer K^+ in vermiculite and illite is almost exclusively present in the clay fraction. If direct release of K^+ from primary K^+-bearing minerals provides a major proportion of plant-available K^+, then the silt and even the sand fraction, as well as the clay fraction, should have measurable impact on the K^+ supply to crops. This was the hypothesis we investigated in pot experiments with four different crop species on five soils.

Materials and methods

Soils

Bulk surface samples of the Balkasar (Udic Haplustalf), Bhalwal (Ustollic Haplargid), Miranpur (Usteric Camborthid), Shahdara (Typic Torrifluvent), and Wazirabad (Udic Haplustalf) soils were collected from the semi-arid plains of Pakistan. The samples were air-dried and ground to pass through a 2-mm sieve. The soils were of medium texture. Their most important properties are reported in Table 1.

Separation of sand, silt, and clay fractions

About 5 kg of each of the dried and ground soils was separated into sand, silt, and clay fractions. To separate them in bulk, the soils were dispersed by mechanical shaking for 16 h on a rapid reciprocating shaker at 1 : 10 soil : water, followed by wet-sieving to separate the sand. The suspended silt and clay fractions were subsequently dispersed by shaking and then separated by centrifugation. The sand, silt, and clay fractions thus obtained for the five soils were air-dried, ground, and mixed thoroughly in order to obtain uniform subsamples for the replicates of the various treatments.

Soil analysis

Total K in the soils and soil fractions was determined according to Bernas (1968) and Follett and Lindsay (1970). Exchangeable K^+ was obtained by extracting the soils and soil fractions with NH_4^+ acetate. Feldspar and mica K was determined by the sodium pyrosulphate fusion method (Kiely and Jackson 1965). A 200-mg sample of either sand, silt, or clay dried at 100 °C, was mixed and fused with 12 – 15 g $NaHSO_4$ in a platinium crucible. The solidified melt was transferred as a cake into a 150-ml beaker using 60 ml 3 *M* HCl. The cake was slaked by gentle boiling and washed three times with 3 *M* HCl in a centrifuge tube. After centrifugation the sediment was transferred into a 500-ml stainless beaker with 150 ml 0.5 *M* NaOH. This suspension was boiled on a hot water-bath for 2.5 min. After cooling, the sediment was washed three times with 3 *M* HCl. The K^+ concentration in the washed sediment and the K^+ concentration in the original sample were used to calculate the feldspar and mica concentrations. The washed sediments contained feldspar K and the total sample the K of the micas + feldspar (Kiely and Jackson 1965).

Plant uptake of K from soil fractions

Each of the sand, silt, and clay fractions recovered from 1 kg of each of the five soils was made up to 1 kg by mixing the fraction separately with prewashed quartz sand. One kilogram of the quartz-soil fraction mixture was placed in each of 60 pots as the medium for plant growth. The pots were plastic, 13 cm high and 13 cm in diameter. Each quartz-soil fraction, subsequently called soil, was set out in four replicates. Solid $Ca(H_2PO_4)$ and $CaSO_4 \cdot 2H_2O$ were mixed thoroughly with the soil to supply P and S at 50 mg kg^{-1} soil each to all four crops, and 50 mg kg^{-1} each of N as NH_4NO_3 and Mg as $MgCl_2$, along with micronutrients in Hoagland's nutrient solution (containing, in μ*M*, 25 H_3BO_3, 2 $MnSO_4$, 2 $ZnSO_4$, 0.5 $CuSO_4$, 0.5 $(NH_4)_6Mo_7O_{24}$ and 50 Fe-ethylenediaminetetraacetic acid) were applied in solution, 50 ml to each pot. No K was applied to any of the pots at any stage of the experiment. Soil moisture was maintained by weighing the pots daily and adding deionized water as required related to the amounts of sand, clay, and silt present in each treatment. The sand was watered to 10% and the silt and clay fractions up to 50% dry weight. Additional nutrients were applied for wheat and maize according to plant growth. After harvesting, the soil from each pot was removed, mixed thoroughly, and repotted before the next crop was planted.

A sequence of crop species was grown, comprising wheat → elephant grass (two cuts) → maize → barley. Twenty seeds of wheat (*Triticum aestivum* cv. Faisalabad 83) sown initially were thinned to 10 plants per pot after germination. The plants were harvested (at tillering stage) 2 months after sowing. Four uniform tufts of elephant grass (*Pennisetum purpureum*) were planted in each pot following the wheat. Two cuttings of elephant grass were obtained during 6 weeks growth and the grass was then replaced by maize (*Zea mays* L. cv. Gohar). Fifteen seeds of maize sown initially were thinned to seven plants per pot after germination. The maize tops were harvested after a months' growth. Then 15 seeds of barley (*Hordeum vulgare*) were sown, which were thinned to 10 plants per

Table 1 Selected characteristics of soils used

Property	Soil series				
	Balkasar	Bhalwal	Miranpur	Shahdara	Wazirabad
Sand (g kg^{-1})	682	205	324	225	722
Silt (g kg^{-1})	197	554	397	694	157
Clay (g kg^{-1})	121	241	281	81	121
Texture	Sandy loam	Silt loam	Clay loam	Silt loam	Sandy loam
pH (H_2O)	7.39	7.73	7.69	7.69	7.74
Organic matter (g kg^{-1})	4.4	17.0	11.3	5.2	4.8
$CaCO_3$ (g kg^{-1})	4.0	29.0	12.0	25.0	5.0
Mineralogy					
Fine clay (<0.2 μm)	Sm	Sm	Chl	Sm	Mica
	HIV	Mica	Mica	Mica	Ver
	Mica	Chl	Kao	Ver	Kao
	Kao	Kao	Ver	Chl	HIV
	Ver	Qtz	Sm	Qtz	–
Coarse clay (2 – 0.2 μm)	Sm	Mica	Mica	Mica	Mica
	Mica	Chl	Chl	Chl	Chl
	HIV	Qtz	Kao	Kao	Qtz
	Kao	–	Qtz	Qtz	–
US Soil Taxonomy	Udic Haplustalf	Ustolic Haplargid	Usteric Camborthid	Typic Torifluvent	Udic Haplustalf

Chl, Chlorite; HIV, hydroxy interlayer vermiculite; Kao, kaolinite; Qtz, quartz; Sm, Smectite; Ver, vermiculite pot after germination. The barley plants were also harvested after 1 month. Neither the roots nor the stubble were removed from the soil when a following crop was sown.

Samples of plant tops and roots were oven-dried at 70 °C to a constant weight for dry matter yield and K analysis. Finely ground tissue samples of all species were digested with a di-acid mixture of $HNO_3 : HClO_4$ (1 : 4). K in the digest was determined by atomic absorption spectroscope.

Statistical analysis

The data obtained for plant dry matter and plant K concentrations were subjected to analysis of variance according to a completely random design and the least significant difference test was used to separate means to determine significant treatment effects (Steel and Torrie 1980).

Results

Table 2 shows total and exchangeable K in the sand, silt, and clay fractions of the five soils. Total K was lowest in the sand and highest in the clay fraction, although the differences between fractions were small. Exchangeable K^+ differed considerably between fractions, being very low in the sand, low in the silt fraction, but average in the clay fraction and considered sufficient for plant growth. In all fractions the mica concentration was exceptionally high, amounting to more than half the total material in the silt and clay fractions. This was an outstanding feature of the soils studied. The concentration of feldspars was rather low compared with the feldspar concentrations of mineral soils from moderate climate zones.

The growth of wheat, maize, and barley was extremely poor on sand, and the plants showed strong symptoms of K^+ deficiency. The leaves turned yellow and necrotic and turgor was so low that the plants did not stand erect. Plants grown on the silt and clay fractions showed K-deficiency symptoms in older leaves, characterized by yellow and necrotic margins (Bergmann 1988). The elephant grass showed no K-deficiency symptoms, not even on the sand fraction, and the plants looked healthy and green.

Plant appearance was reflected by the K^+ concentrations in the above-ground plant matter (Table 3). With some exceptions, K^+ concentrations in wheat, maize, and barley tops were much lower than required for optimum growth, regardless of whether the plants were grown on the sand, silt, or clay fractions. The optimum range of K^+ in grasses during the vegetative stage is about 25–30 mg K g^{-1} dry matter (Bergmann 1988). Except for the elephant grass, such high K concentrations were found only in barley grown on the clay fraction of the Bhalwal, Miranpur, and the Wazirabad soils. The clay fractions of these soils were exceptionally high in mica. The K concentration in the first and second cuts of elephant grass was sufficient in plants grown on all three soil fractions.

Yields of above-ground plant matter are shown in Table 4. Those obtained from the sand fraction were very poor, and the yields of wheat, maize, and barley on the silt and clay fractions were several times higher than on sand. The yields from the silt fraction were at least as high as those from the clay fraction, and in the case of maize the dry matter harvested from the silt was significantly higher than that from clay. Again, the elephant grass was an exception; the yields harvested did not differ between soil fractions or between cuttings. Nevertheless, these yields were low.

From the data in Tables 2 and 4 it is clear that growth on silt was at least as good as on clay. Since the silt material per pot formed a larger percentage than the clay material per pot (Table 1), and the mica concentration in the silt was almost as high as in the clay (Table 2), much more mica was present in the pots containing silt fraction than in those containing clay. However, the concentration of exchangeable K^+ was on average three times higher in the clay than in the silt (Table 2).

In Table 5 the K^+ uptake of the four plant species from the Balkasar clay fraction is compared with the K^+ uptake from the Miranpur silt fraction. From the data it is clear that K^+ uptake was more influenced by the mica then by the exchangeable K^+. The K^+ uptake of the first

Table 2 Total and exchangeable potassium in minerals of the sand, silt, and clay fraction

	Total K ($g\ kg^{-1}$)	Exchangeable K ($mg\ kg^{-1}$)	K-bearing minerals ($g\ kg^{-1}$)	
			Mica	Feldspar
Sand	18 (15–21)	17 (14–22)	350 (287–416)	47 (11–76)
Silt	23 (19–25)	70 (17–132)	534 (439–581)	14 (12–17)
Clay	25 (18–30)	230 (65–280)	564 (398–708)	26 (12–39)

Means (range) for five soils

Table 3 K concentrations ($mg\ K\ g^{-1}$ dry matter) in above-ground plant matter of species grown on sand, silt, and clay fractions

Species	Sand	Silt	Clay
Wheat	4.48 (3.3–5.7)	7.88 (6.3–9.9)	10.5 (5.5–17.6)
Ele. grass			
First cut	26.1 (24–29)	26.7 (24–32)	30.9 (25–39)
Second cut	36.4 (32–42)	34.9 (32–37)	32.8 (28–37)
Maize	8.08 (5.8–9.4)	7.9 (6.5–9.0)	8.52 (6.2–12)
Barley	10.0 (8.0–12)	16.9 (11–23)	21.1 (9.6–30)

Means (range) for fractions from five different soils. Ele. grass, Elephant grass. Least significant difference (0.01) = 2.30 for soil fraction × plant species interaction

Table 4 Yield (g dry matter pot^{-1}) of plant species grown on sand, silt, and clay fractions

Species	Sand	Silt	Clay
Wheat	0.68 (0.42 – 1.43)	4.18 (3.05 – 5.36)	4.28 (2.11 – 5.71)
Ele. grass			
First cut	0.95 (0.87 – 1.16)	0.96 (0.79 – 1.14)	0.88 (0.64 – 1.21)
Second cut	0.71 (0.59 – 0.85)	0.79 (0.54 – 1.01)	0.88 (0.64 – 1.21)
Maize	1.91 (0.69 – 2.77)	4.08 (2.57 – 4.88)	3.37 (3.01 – 4.20)
Barley	0.43 (0.23 – 0.71)	1.35 (1.13 – 1.35)	1.09 (0.87 – 1.36)

Means (range) for fractions from five different soils. Ele. grass, Elephant grass. Least significant difference (0.01) = 0.30 for means of dry matter yield from soil fraction plant interaction

crop (wheat) was already higher than the quantity of exchangeable K^+ in the pot; the following crops therefore exclusively used non-exchangeable K^+. The level of non-exchangeable K^+ was much higher in the Miranpur silt fraction than in the Balkasar clay fraction, and total K^+ uptake by the crops was much higher from the Miranpur silt fraction than from the Balkasar clay fraction (Table 5). The difference was particularly evident in the last grown crop (barley), for which the K^+ uptake from the Miranpur silt fraction was almost four times higher than from the Balkasar clay fraction.

Discussion

Although the soils investigated differed in texture (Table 1), their chemical composition appeared to be rather uniform, with mica being the dominant mineral. In the silt and clay fractions mica made up more than 50% of total silt or clay, respectively, and even in the sand fraction more than one-third was mica (Table 2). From our analysis it was not clear whether this was mainly a di-or tri-octahedral mica. The latter weathers more easily and since K^+ originating from mica contributed much to the K^+ supply of our crops we assumed that the tri-octahedral mica type was dominant. The plant yields obtained from the silt fraction were at least as high as those from the clay fraction (Table 4), although the concentration of exchangeable K^+ was on average about three times higher in the clay than in the silt fraction. From this finding we conclude that exchangeable K^+ was less important for plant nutrition than the K^+ released from mica. This assumption is well supported by the data in Table 5 showing that K^+ uptake from the Miranpur silt, which was rich in mica, was much higher than from the Balkasar clay, which was relatively low in mica but high in exchangeable K^+. Exchangeable K^+ was more or less taken up by the first crop (wheat) while the following crops had to use the K^+ released by K^+-bearing minerals, of which the main representative was mica. In the pots containing Miranpur silt, much mica was present in the root medium, and hence the K^+ uptake by crops barely decreased from one crop to another in the sequence (Table 5). However, with the Balkasar clay fraction, which was relatively low in mica, the K^+ uptake clearly decreased from one crop to the next in the sequence of crop species grown. Thus the last crop (barley) grown on the Miranpur silt took up almost four times more K^+ than that grown on the Balkasar clay.

From this finding we conclude that for these Aridisols rich in mica, exchangeable K^+ alone is a poor indicator of K^+ availability to plants and the mica concentration of the silt and clay fraction is of high relevance for supplying the plants with K^+. In both fractions the absolute mica concentration was high and since the proportion of silt + clay amounted to about 70 – 80% of the total soil in three of the five soils investigated the contact surface between roots and mica was relatively large.

Except for the elephant grass, all species grown on all soil fractions showed K^+-deficiency symptoms which were particularly severe on the sand fraction. Obviously, the larger particles of this fraction are less likely to release K^+ because the surface is less specific than the finer mica particles of the silt, and particularly of the clay fraction (Bajwa 1989). The fact that the K^+ concentrations found in the tops of wheat, maize, and barley were suboptimal should not lead to the conclusion that under field conditions, also, these soils do provide not enough K^+ for crops. In the present study the soil fractions were diluted with quartz sand and the rooting volume of crops cultivated in pots is very limited compared with the rooting volume in the field.

The reason why the elephant grass showed no K^+-deficiency symptoms is not yet understood. This interesting problem needs further investigation.

Table 5 Comparison of K uptake (mg K pot^{-1}) from a growth medium relatively low in mica (Balkasar) and one high in mica (Miranpur)

Soil	Wheat	Elephant grass		Maize	Barley	Total
		First cut	Second cut			
Balkasar, clay	37.3	25.9	28.9	18.7	7.7	95
Miranpur, silt	43.4	21.4	34.4	37.5	28.6	165

Exchangeable K: Balkasar, clay fraction 32.4 mg pot^{-1}; Miranpur, silt fraction 23.4 mg pot^{-1}; Mica: Balkasar, clay fraction 48 g pot^{-1}; Miranpur, silt fraction, 204 g pot^{-1}

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