Potassium Pool Equilibration in Some Calcareous Soils as Affected by Long Term Rice Cultivation Systems

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ABSTRACT

To study the effect of rice cultivation systems on the equilibration among different forms of potassium, surface (0–20 cm) and subsurface (20–40 cm) horizons of paddy and adjacent non-paddy soils from 10 regions of Fars province with rice cultivation history were collected. Different soil properties and K forms including soluble, exchangeable, non-exchangeable, mineral and total K were determined. Results indicated that soluble K in paddy soils was significantly lower than non-paddy soils (4.4 vs. 7.0 mg kg^{-1}). Non-paddy soils had higher exchangeable and non-exchangeable K than paddy soil (268 vs. 200 and 771 vs. 638 mg kg^{-1}, respectively). Mineral and total K increased in paddy cultivation from 4399 to 5202 and from 5445 to 6044 mg kg^{-1}, respectively. With rice cultivation, K ions were more concentrated in mineral K rather than non-paddy soils (86 vs. 81% of total K). Exchangeable K in surface horizons was higher than subsurface horizons for paddy and non-paddy soils; while this difference was not significant for other K forms. Non-exchangeable, mineral and total K was significantly correlated with illite content. It is concluded that rice cultivation decreased more available forms of K and this should be considered for K fertilizers recommendation in paddy cultivation systems.

Keywords: Paddy soils, exchangeable K, non-exchangeable K, mineral K, calcareous soils

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INTRODUCTION

Long term rice cultivation management may affect potassium (K) pool distribution as well as soil chemical and physical properties. These management practices, such as plowing and puddling, artificial submergence and drainage, manuring, liming and fertilization have obvious impacts on soil properties (Ponnamperuma, 1972; Yu, 1985; Kirk, 2004) and thereby K equilibration among soluble, exchangeable, non-exchangeable and mineral K (Havlin *et al.*, 2005). Exchangeable and solution K (available K forms) equilibrate rapidly, whereas nonexchangeable potassium equilibrates very slowly with the exchangeable and solution forms. Transfer of potassium from the mineral fraction to any of the other three forms is extremely slow in most soils, and this K is considered essentially unavailable to crops during a single growing season (Havlin *et al.,* 2005).

The irrigation water flowing from paddy fields contains 1.5–1.7 g L^{-1} of suspended material, which is richer in clay and fine particles than the bulk soil (Zhang and Gong, 1998) and may add K to paddy soils. Irrigation water in arid regions may contain high amount of soluble K. However, K leaching by irrigation water may be significant. Removal of K by plant may also affect K pool distribution in soils. The rate of K supply or release to soluble and exchangeable forms is largely governed by the weathering of K-bearing micas and feldspars. The gradual release of K from positions in the mica lattice results in the formation of illite and eventually vermiculite and smectite (Havlin *et al.,* 2005).

Hu and Wang (2004) concluded that non-exchangeable K was an important K source for rice and K application caused an annual decrease in the concentration of available K in the soil tested; whereas an increase was observed in non-exchangeable K. Contribution of the non-exchangeable K towards total potassium removal by rice may be higher than 90% in the absence of applied K. However, application of K resulted in lesser uptake from non-exchangeable pool (Swarup and Chhillar, 1986). Dobermann *et al.* (1996) due to little or no K fertilizers application for some rice cultivated soils of Asia concluded that there was significant depletion of soil K reserves at many sites.

Many factors affecting K pool distribution in calcareous soils. Generally, K distribution in soils is related to many soil properties including soil minerals, calcium carbonate content, CEC, clay content, soil order, organic carbon, total calcium, and soil salinity (Sharpley, 1989; Natarajan and Renukadevi, 2003; Najafi-Ghiri *et al.*, 2011b; Reza *et al.*, 2014; Shakeri and Abtahi, 2018). Najafi-Ghiri *et al.* (2011b) and Nabiollahy *et al.* (2006) found a significant relationship between soil K forms and mica or illite and concluded that illite is the dominant clay that controls K pool content in the calcareous soils.

Although soils in arid and semiarid regions of Iran contain large quantities of exchangeable K (150–593 mg kg^{-1}), the content of this form of K in agricultural soils was decreased since 20 years ago, because of the intensive crop production and little or no application of K fertilizers (Balali and Malakouti, 1998). When soluble and exchangeable K are decreased, K from non-exchangeable form is released to the exchangeable form and become an important resource for providing K to plants. Lowland in southern Iran (especially in Fars province) is used for a cropping sequence of flooded paddy rice followed by a non-flooded crop. The uplands have been exclusively used for non-flooded crop production. This enables us to study the K pool distribution in surface and subsurface horizons of paddy and non-paddy soils in a unique way.

We hypothesized that rice cultivation changes different soil properties and K pool equilibration in calcareous soils of Iran. Therefore, the main purposes of this study were to compare K pool distribution among soluble, exchangeable, non-exchangeable K and mineral K in non-paddy and paddy soils and to find the most influential soil characteristics that predict different K pool in the non-paddy and paddy soils.

MATERIALS AND METHODS

Site Description and Soil Sampling

Soils collected from Fars province, southern Iran (Figure 1) were investigated in order to determine the changes in K pool distribution by long term rice cultivation. We tried to select 10 regions with different climatic conditions and soil characteristics. The elevation of the studied area varies 500–4,409 m above sea level. Annual precipitation ranges 50–1,185 mm. Mean annual temperature ranges from 10.5 to 24°C. The whole study area is a part of the Zagros orogenic area and consists of carbonatic and gypsiferous alluvium. The current use of the studied soils is rice cultivation or rangeland. This study was conducted in ten regions. In each region, a paddy soil (with >100 years rice cultivation history) and a non-paddy soil were identified and selected. Soil samples from two depths (0–20 and 20–40 cm horizons) were collected with auger, air-dried and sieved (<2 mm) for laboratory analyses. Soil sampling was done about two months after rice harvesting for K pool equilibration.

Figure 1 Location of Fars province, southern Iran

Laboratory Analyses

Soil pH was measured in saturated soil paste using deionized water. Electrical conductivity (EC) was measured in the soil saturated extract. Organic carbon content was measured by dichromate oxidation method (Nelson and Sommers, 1996). Calcium carbonate equivalent (CCE) was determined by acid neutralization (Loppert and Suarez, 1996). Particle-size distribution was measured by the hydrometer method (Gee and Bauder, 1986). Cation exchange capacity (CEC) was determined by saturating of soil with 1 M sodium acetate at pH 8.2 and replacing sodium by subsequent washing with 1 M ammonium acetate at pH 7 (Sumner and Miller, 1996).

Different forms of K were determined by the methods of Helmeke and Sparks (Helmke and Sparks, 1996). Water soluble K was determined in the saturated extract. Exchangeable K was extracted with four times extractions of 5 g soil with 25 mL of 1.0 M NH_4OAc (pH 7.0) after 10 min shaking. Non-exchangeable K was determined by extraction of 2.5 g soil sample with 25 ml boiling 1.0 M HNO_3 for 1 h and then soluble and exchangeable K were deducted from it. Total K was determined following digestion (383°K) of 0.5 g soil sample with 10 ml of 48% HF and 1 ml of aqua regia. Potassium was measured on all filtrated extracts by Corning 405 flame photometer.

Mineralogical Analysis

The methods of Kittrick and Hope (1963), Jackson (1975) and Mehra and Jackson (1960) were used for removal of chemical cementing agents and separation of the soil fractions. Clay samples were X-rayed, with a Philips diffractometer. The content of minerals was determined using the method of Johns *et al.* (1954).

Statistics Analyses

Statistical analysis was performed by the software SPSS for Windows v. 15 (two-tailed for test of correlation significance). Means comparison of K forms in paddy and non-paddy soils was performed by paired-samples T-test.

RESULTS AND DISCUSSION

Soil Characteristics

Mean values of some properties of the studied soil are shown in Table 1. Generally, significant differences were found between properties of paddy and non-paddy soils in surface and subsurface horizons. The pH value of surface and subsurface horizons of paddy soils were significantly lower than that of non-paddy soils. There was no significant difference between pH values of surface and subsurface horizons. Surface horizon of paddy soils had more salinity than that of non-paddy soils (means of 1.54 vs. 1.10 dS m^{-1}). Generally, the texture of paddy soils was finer than that of non-paddy soils. Cation exchange capacity of paddy soils was higher than that of non-paddy soils and this may be due to the higher clay and organic matter contents. Paddy soils had more calcium carbonate equivalent than non-paddy soils.

Table 1 Mean values (for 10 soils) of some soil properties

Soils	Depth (cm)	pH	EC (dS m^{-1})	Clay (%)	Silt (%)	Sand (%)	CEC (cmol+ kg^{-1})	OC (%)	Gypsum (%)	CCE* (%)
Non-paddy	0–20	7.85^{a}	1.10^{b}	35^{c}	38^{a}	27^{a}	13.4^{c}	0.8^{b}	0.7^{a}	59^{a}
	20–40	7.90^{a}	0.90^{b}	37^{c}	32^{ab}	31^{a}	12.3^{d}	0.5^{c}	0.6^{a}	60^{a}
Paddy	0–20	7.42^{b}	1.54^{a}	43^{b}	35^{ab}	22^{b}	16.0^{a}	1.1^{a}	0.7^{a}	55^{b}
	20–40	7.56^{b}	1.02^{b}	48^{a}	30^{b}	21^{b}	14.7^{b}	0.7^{b}	0.6^{a}	55^{b}

Note: *Calcium carbonate equivalent
Means followed by different letters in each column are significantly different at $P < 0.05$ by t-test

Clay Mineralogy

Mineralogical analysis of soils indicated that smectites, chlorite, illite, palygorskite and interstratified minerals were the dominant clay minerals occurred in the studied soils (Table 2). This is in consistent with findings of Najafi-Ghiri and Abtahi (2012) Owliaie *et al.* (2006) and Khormali and Abtahi (2003) for calcareous soils of southern Iran. Although, all of the studied soils had similar clay minerals, the relative abundance varied among soils. Smectite were the dominant mineral of the clay fraction of paddy soils; while palygorskite was not found. On the other hand, non-paddy soils had a high content of palygorskite. Chlorite and illite contents in paddy and non-paddy soils showed no significant difference.

Table 2 Clay mineralogy (<0.002 mm) of the surface and subsurface horizons of paddy and non-paddy soils

Soils	Depth (cm)	Smectite	Illite	Chlorite	Palygorskite	Mixed
Non-paddy	0–20	++	+++	+++	++	tr*
	20–40	++	++	+++	++	+
Paddy	0–20	++++	++	+++	tr*	+
	20–40	+++	++	++++	tr*	+

Note: + Relative abundance of clay minerals, * trace

Potassium Pool Content and K Pool Distribution

The contents of different K forms including soluble, exchangeable, non-exchangeable, and mineral in surface and subsurface horizons of paddy and non-paddy soils are shown in Table 3. Soluble K contents varied widely in the studied soils; but the values of soluble K were normally distributed, with low skewness (0.90) and kurtosis (0.35). Except for soil 5, soluble K content in surface horizon of paddy soils was significantly lower than that of non-paddy soils (4.4 vs. 7.0 mg kg^{-1}). On the other hand, there was no significant difference in soluble K between subsurface horizon of paddy and non-paddy soils (2.4 and 3.0 mg kg^{-1}, respectively). Generally, the content of soluble K in the studied soils was lower than 13 mg kg^{-1}. The content of soluble K in non-saline soils of southern Iran is lower than 20 mg kg^{-1} and the higher content is related to the saline soils and cultivated soils with high K fertilizers application (Najafi-Ghiri *et al.,* 2011b). Soluble K in surface and subsurface horizons of non-paddy soils differed significantly ($P < 0.05$); however this difference was not significant for paddy soils. Najafi-Ghiri *et al.* (2011b) for 57 non-paddy calcareous soils of southern Iran and Natarajan and Renukadevi (2003) for some major soil series of Tamil Nadu indicated that amounts of K was decreased with depth of soil profile. This decrease may be due to the upward capillary movement of K^+ due to evapotranspiration, K release from OM and highly-weathered K-bearing minerals and K fertilizers application to surface horizon (Najafi-Ghiri *et al.,* 2011b).

As an average, soluble K constituted 0.14% (ranged 0.03–0.33%) and 0.08% (ranged 0.01–0.11%) of total K in non-paddy and paddy soils, respectively, and this difference was significant ($P < 0.05$). This finding is consistent with findings of Najafi-Ghiri *et al.* (2011b) for calcareous soils of southern Iran. The highest and lowest percentages of soluble K were observed in surface horizon of non-paddy soil in region 3 and subsurface horizon of paddy soil in region 7, respectively. Percentage of soluble K in subsurface horizons of paddy and non-paddy soils showed no significant difference.

Significant relationships were found between soluble K and OC and clay. The results of stepwise multiple regressions indicated that OC and clay are the most influential soil characteristics that predict soluble K in the non-paddy and paddy soils, respectively, as follows:

For non-paddy soils:
Soluble K = -2.5 + 11.5(OC) $R^2 = 0.60^{**}$
For paddy soils:
Soluble K = 13.1-0.2(Clay) $R^2 = 0.46^{*}$

The content of exchangeable K in the surface horizons of paddy and non-paddy soils ranged 141–276 and 173–351 mg kg^{-1}, respectively (Table 3) and distributed normally (with skewness and kurtosis of 0.6 and -0.6, respectively). These values support findings of Najafi-Ghiri *et al.* (2011b) for some calcareous soils of southern Iran and Nabiollahy *et al.* (2006) for some soils of western Iran and were higher than values reported by Wani (2013) for 10 soils of lesser Himalayas (47–172 mg kg^{-1}), Reza *et al.* (2014) for some soils of the North-Eastern region of India (27–210 mg kg^{-1}) and Ajiboye *et al.* (2015) for six wetland soils in Abeokuta, southwest Nigeria (20–80 mg kg^{-1}). There is a significant difference ($P < 0.05$) between surface horizons of paddy and non-paddy soils in exchangeable K (except soil 4); while this difference was not significant for subsurface horizons (Table 3). Generally, the content of exchangeable K in surface soils was significantly higher than that in subsurface soils for all samples. It may be due to the higher weathering rate of K-bearing minerals and release and adsorption of K by mineral and organic exchange sites in surface soils (Najafi-Ghiri *et al.,* 2011a). Exchangeable K constituted 1.8–7.7% of total K in the studied soils. The highest and lowest percentages of exchangeable K were observed in surface horizon of non-paddy soil in region 2 and subsurface horizon of paddy soil in region 10. As an average, exchangeable K constituted 5.1% of total K in non-paddy soils and was significantly higher than that in paddy soils (3.3%). The percentage of exchangeable K in surface soils was significantly higher than that in subsurface soils ($P < 0.05$). This may be due to the release of K from mineral forms as a result of weathering in the surface soils. Exchangeable K had significant relationships ($P < 0.05$) with pH, clay and sand content. The stepwise multiple regressions indicated that pH-clay and sand are the most influential soil characteristics that predict exchangeable K in the non-paddy and paddy soils, respectively, as follows:

For non-paddy soils:

$$\text{Exchangeable K} = -1158 + 2.7(\text{Clay}) + 169(\text{pH}) \quad R^2 = 0.77^{**}$$

For paddy soils:

$$\text{Exchangeable K} = 247 - 2.2(\text{Sand}) \quad R^2 = 0.52^{*}$$

Table 3 Content of different K forms, mg kg^{-1} and K pool distribution in surface and subsurface horizons of paddy and non-paddy soils of Fars province, southern Iran

Region	Cultivation	Depth (cm)	K pool content (mg kg^{-1})					KSP**,	K pools distribution (%)			
			SK*	EK*	NEK*	MK*	TK*	(%)	SK*	EK*	NEK*	MK*
1	Non-paddy	0–20	6.7	307	612	4,637	5,563	6.2	0.12	5.5	11.0	83
		20–40	1.9	294	664	5,493	6,453	6.0	0.03	4.6	10.3	85
	Paddy	0–20	5.9	212	433	5,499	6,150	3.6	0.10	3.5	7.0	89
		20–40	5.4	172	552	5,602	6,331	3.2	0.09	2.7	8.7	88
2	Non-paddy	0–20	6.1	215	461	2,587	3,269	5.5	0.19	6.6	14.1	79
		20–40	2.5	199	444	1,927	2,572	5.3	0.10	7.7	17.3	75
	Paddy	0–20	1.7	151	407	4,614	5,174	2.8	0.03	2.9	7.9	89
		20–40	0.9	168	377	5,485	6,031	3.1	0.01	2.8	6.2	91
3	Non-paddy	0–20	13.0	276	521	3,131	3,940	6.3	0.33	7.0	13.2	79
		20–40	4.8	256	516	3,471	4,248	6.5	0.11	6.0	12.1	82
	Paddy	0–20	10.1	191	359	3,792	4,352	3.5	0.23	4.4	8.2	87
		20–40	0.9	129	416	3,344	3,890	2.9	0.02	3.3	10.7	86
4	Non-paddy	0–20	12.0	173	512	4,865	5,563	4.4	0.22	3.1	9.2	87
		20–40	5.8	147	534	4,423	5,110	4.3	0.11	2.9	10.4	87
	Paddy	0–20	8.2	169	474	5,071	5,721	3.2	0.14	3.0	8.3	89
		20–40	2.8	158	459	5,530	6,150	3.6	0.04	2.6	7.5	90
5	Non-paddy	0–20	4.0	198	480	3,108	3,790	4.8	0.10	5.2	12.7	82
		20–40	2.3	135	468	3,539	4,145	3.9	0.05	3.3	11.3	85
	Paddy	0–20	3.9	141	490	4,418	5,054	2.5	0.08	2.8	9.7	87
		20–40	1.6	128	521	4,020	4,671	2.7	0.03	2.7	11.2	86
6	Non-paddy	0–20	8.1	351	1,596	4,706	6,661	6.0	0.12	5.3	24.0	71
		20–40	2.0	321	1,294	4,474	6,091	6.0	0.03	5.3	21.2	73
	Paddy	0–20	2.6	224	927	5,645	6,799	3.5	0.04	3.3	13.6	83
		20–40	4.3	141	901	5,104	6,150	2.4	0.07	2.3	14.7	83

Table 3 Continues

Region	Cultivation	Depth (cm)	K pool content (mg kg^{-1})					KSP**,	K pools distribution (%)			
			SK*	EK*	NEK*	MK*	TK*	(%)	SK*	EK*	NEK*	MK*
7	Non-paddy	0–20	2.4	306	1,370	4,506	6,184	5.3	0.04	4.9	22.2	73
		20–40	0.6	184	1,118	4,932	6,235	3.1	0.01	2.9	17.9	79
	Paddy	0–20	2.0	267	1,255	4,746	6,271	4.1	0.03	4.3	20.0	76
		20–40	0.3	161	943	5,227	6,331	2.7	0.01	2.5	14.9	83
8	Non-paddy	0–20	2.7	343	1,115	5,301	6,761	5.8	0.04	5.1	16.5	78
		20–40	2.8	258	1,095	5,097	6,453	4.9	0.04	4.0	17.0	79
	Paddy	0–20	2.1	208	1,017	6,164	7,391	2.9	0.03	2.8	13.8	83
		20–40	2.4	198	954	6,127	7,282	2.8	0.03	2.7	13.1	84
9	Non-paddy	0–20	3.4	223	566	5,770	6,563	3.5	0.05	3.4	8.6	88
		20–40	2.7	124	494	5,435	6,056	2.1	0.04	2.0	8.2	90
	Paddy	0–20	2.2	177	566	6,268	7,012	2.4	0.03	2.5	8.1	89
		20–40	1.9	200	404	6,662	7,267	2.8	0.03	2.7	5.6	92
10	Non-paddy	0–20	11.6	284	481	5,374	6,150	4.1	0.19	4.6	7.8	87
		20–40	4.5	141	445	5,572	6,162	2.4	0.07	2.3	7.2	90
	Paddy	0–20	5.3	255	452	5,801	6,514	3.4	0.08	3.9	6.9	89
		20–40	3.4	118	380	5,951	6,453	1.7	0.05	1.8	5.9	92
Mean	Non-paddy	0–20	7.0^{a}	268^{a}	771^{a}	4,399^{b}	5,445^{b}	5.2^{a}	0.14^{a}	5.1^{a}	13.9^{a}	81^{c}
		20–40	3.0^{b}	206^{bc}	707^{a}	4,436^{b}	5,352^{b}	4.4^{b}	0.06^{b}	4.1^{b}	13.3^{a}	83^{bc}
	Paddy	0–20	4.4^{b}	200^{b}	638^{b}	5,202^{a}	6,044^{a}	3.2^{c}	0.08^{b}	3.3^{b}	10.4^{b}	86^{ab}
		20–40	2.4^{b}	157^{c}	591^{b}	5,305^{a}	6,056^{ab}	2.8^{c}	0.04^{b}	2.6^{c}	9.8^{b}	87^{a}

Note: * SK, EK, NEK, MK, TK, soluble, exchangeable, non-exchangeable, mineral, total potassium respectively. ** KSP, potassium saturation percentage.
Means for each column followed by different letters are significantly different at $P < 0.05$ by Duncan's test

Potassium saturation index (KSP), calculated as a ratio of exchangeable potassium divided by the cation exchange capacity (as percentage), is another index for assessment of K status (Havlin *et al.,* 2005). In fact, KSP shows the priority of K held in the exchange sites (clay and OM). The values of KSP in surface horizons of non-paddy and paddy soils differed significantly and ranged 3.5–6.3 and 2.4–4.1%, respectively. These values for subsurface horizon of non-paddy and paddy soils were 2.1–6.5 and 1.7–3.6%, respectively and differed significantly. These results are comparable with finding of Najafi-Ghiri *et al.* (2011b) for some soils of Iran (mean of 4.0%) and Al-Zubaidi (2001) for Iraqi soils (mean of 4.51%) and higher than the finding of Al-Zubaidi *et al.* (2008) for some Lebanese soils (mean of 1.73%).

Nonexchangeable K (NEK) is the major portion of the reserve of available K in soil and a primary factor in determining soil K fertility (Srinivasarao *et al.,* 2006). Non-exchangeable K in surface horizons of paddy and non-paddy soils ranged 359–1,255 and 461–1,596 mg kg^{-1}, respectively, with significant difference (except for soils 5 and 9). The content of non-exchangeable K in subsurface horizons of paddy soils was also significantly lower than that of non-paddy soils ($P < 0.05$). Non-exchangeable K release from subsoil is important because many crops can obtain substantial amounts of K from lower layers, especially deep-rooted crops. The content of non-exchangeable K in surface and subsurface soils showed no significant difference. This is consistent with finding of Najafi-Ghiri *et al.* (2011b) who indicated that non-exchangeable K content in surface and subsurface soils of southern Iran ranged 206–1,521 and 120–1,473 mg kg^{-1}, respectively. Non-exchangeable K constituted 5.6–24.0% of total K in the studied soils. The lowest and highest percentages of non-exchangeable K were observed in subsurface horizon of paddy soil in region 9 and surface horizon of non-paddy soil in region 6. As shown in Table 3, non-exchangeable K percentage in non-paddy soils was significantly larger than that in paddy soils ($P < 0.05$). There is no significant difference between surface and subsurface soils in non-exchangeable K percentage.

Non-exchangeable K was significantly correlated with clay, sand and CCE (r of 0.57**, -0.39* and -0.65**, respectively). Najafi-Ghiri *et al.* (2011b) found significant relationship between non-exchangeable K and CCE, clay and CEC in soils of Iran. The stepwise multiple regressions indicated that clay-sand and clay are the most influential soil characteristics that predict soluble K in the non-paddy and paddy soils, respectively, as follows:

For non-paddy soils:
NEK = -2,590 + 68(Clay) + 35(Sand) $R^2 = 0.92$**
For paddy soils:
NEK = -582 + 28(Clay) $R^2 = 0.79$*

The major sources of nonexchangeable K in soils are K rich 2:1 clay minerals such as micas and vermiculite (Srinivasarao *et al*., 2006). Since mica, illite, smectite and vermiculite are the main clay minerals present in arid and semi-arid soils in Iran (Khormali and Abtahi, 2003), the release rate of K from non-exchangeable positions to readily available forms might be considerable. Sparks (1987) stated that availability of non-exchangeable K did not depend on the quantity of interlayer K, but depended primarily on the rate at which it can be released into more labile forms.

Mineral and total K in paddy soils was significantly higher than those in non-paddy soils (except for soils 4, 6 and 7). Some researchers found a significant relationship between different forms of K and clay content. Paddy soils in the studied regions had relatively higher clay content than non-paddy soils maybe due to the artificial accumulation of dredged fine materials on the surface horizon. The irrigation water flowing from paddy fields contains 1.5–1.7 g L^{-1} of suspended material, which is richer in clay and fine particles than the bulk soil (Zhang and Gong, 1998). Surface and subsurface horizons showed no significant difference in the contents of mineral and total K. Mineral K constituted 71–92% of total K in the studied soils. The largest content was found in subsurface horizon of paddy soil in region 9; while the surface horizon of non-paddy soil in region 6 had the lowest content. Generally, mineral K percentage in paddy soils was significantly larger than that in non-paddy soil ($P < 0.05$). There is no significant difference between surface and subsurface horizons in the percentage of mineral K (83.5 vs. 85%). Mineral and total K had significant correlations with EC, clay, silt, sand, CEC and CCE.

For non-paddy soils:
Mineral K = 5,939 – 57(Sand) $R^2 = 0.66$**
For paddy soils:
Mineral K = 17,012 – 40(Sand) – 1,474(pH)
$R^2 = 0.86$**
For non-paddy soils:
Total K = 7,984 – 87(CCE) + 192(CEC)
$R^2 = 0.92$**
For paddy soils:
Total K = 17,035 – 55(Sand) –1,321(pH)
$R^2 = 0.89$**

Generally, total K in paddy soils was significantly higher than that in non-paddy soils. This may be due to the addition of clay particles (including K-bearing minerals) and soluble K from irrigation water (Zhang and Gong, 1998), K release from organic matter and plant residue (Havlin *et al.,* 2005) and dilution effect of carbonates (Najafi-Ghiri *et al.,* 2011a) that leached from paddy soils. Calcium carbonate as an inert material in soils had a negative correlation with K content, because of dilution effect (Najafi-Ghiri and Abtahi, 2011). Nevertheless, the content of soluble, exchangeable and non-exchangeable K in paddy soils was significantly lower than those in non-paddy soils. This may be due to the removal of K by plant uptake and leaching of soluble K by irrigation water. This caused the relative decrease in soluble, exchangeable and non-exchangeable K and relative increase of mineral K in paddy soils rather than non-paddy soils. Thus mineral K constituted higher percentage of total K (more than 86%) in the studied paddy soils. However this difference was not significant for soils 4, 9 and 10. Generally, significant relationships were found between exchangeable and non-exchangeable K, non-exchangeable and total K and mineral and total K, regardless of land use and soil depth (Figure 2). This means that with increasing content of any form of K, other forms of K are also increased. The positive correlations among the forms of K indicated that there is a dynamic equilibrium between different K forms (Havlin *et al.,* 2005; Najafi-Ghiri and Abtahi, 2011). Relationships among different K forms have been reported by many researchers for many different soils like Najafi-Ghiri *et al.* (2011b) for some calcareous soils of Iran, Najafi-Ghiri and Abtahi (2011) for some Vertisols of southern Iran, Sharpley (1989) for 102 soils from the continental USA and Puerto Rico, Nabiollahy *et al.* (2006) for some calcareous soils of western Iran and Padole, Shakeri and Abtahi (2018) for some calcareous soils of Kohgiluyeh and Boyer-Ahmad Province in Southwest Iran and Mahajan (2003) for some swell-shrink soils of Vidarbha, Maharashtra.

Clay mineralogical study and its relationships with different forms of K indicated that the contents of non-exchangeable, mineral and total K were significantly correlated with illite content in the clay fraction, regardless of land use and soil depth (Figure 3). Illite is an important K-bearing mineral in calcareous soils of southern Iran, and K ions may be released from illite due to decrease in soluble K concentration (Najafi-Ghiri *et al.,* 2011a). Relationships between K forms and illite have been previously reported by some researchers for calcareous soils (Nabiollahy *et al.,* 2006; Najafi-Ghiri *et al.,* 2011b; Shakeri and Abtahi, 2018). Generally, illite constituted 20–35% of the clay fraction and its content in non-paddy soils was more than that in paddy soils (Table 2). Najafi-Ghiri *et al.* (2011b) stated that many properties like climatic conditions, soil orders, depth, agricultural activity, leaching, and some soil properties like particle size distribution, soil salinity, calcium carbonate equivalent, and cation exchange capacity affect K-bearing minerals (micas and feldspars) distribution, transfer, and transformation in soils and thereby K pool distribution of the soils. No relationship was found between soluble and exchangeable K with clay mineralogy; in fact, many different processes may affect soluble and exchangeable K in soil (Najafi-Ghiri *et al.,* 2011b); thus clay mineralogy alone cannot predict the contents of these K forms.

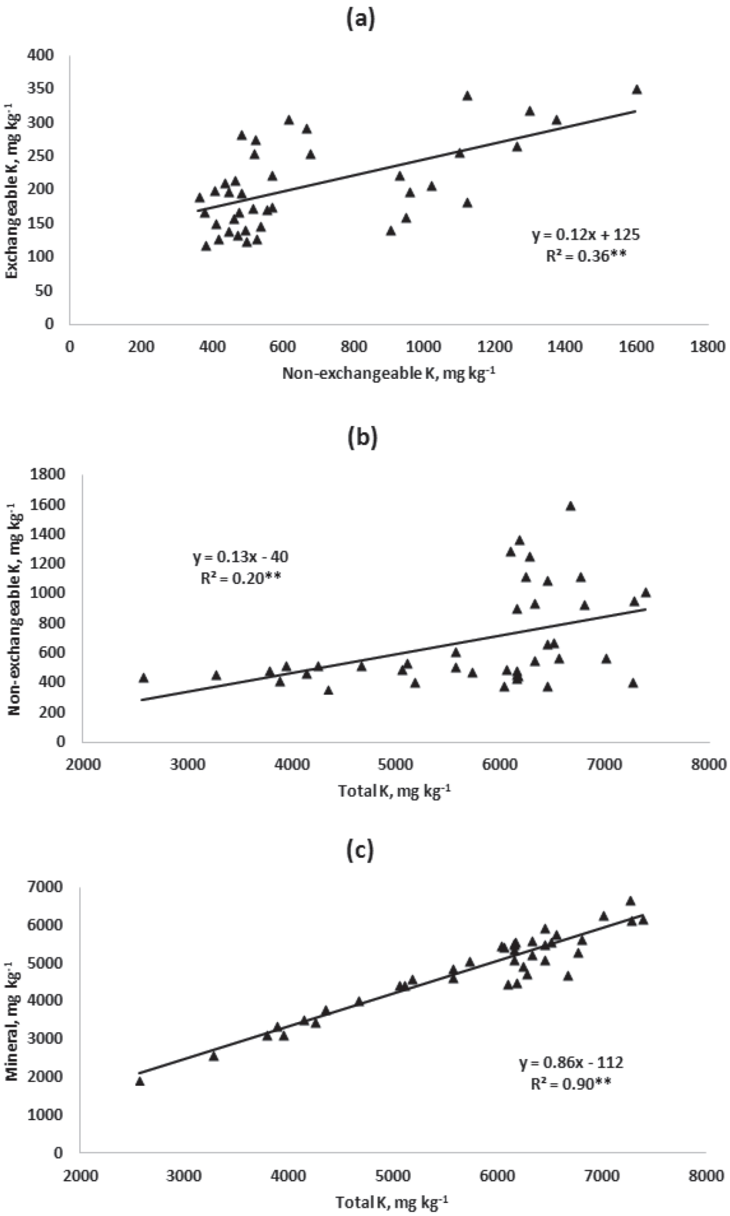

Figure 2 Relationships between exchangeable and non-exchangeable K (a), non-exchangeable and total K (b) and mineral and total K (c) for all soil samples

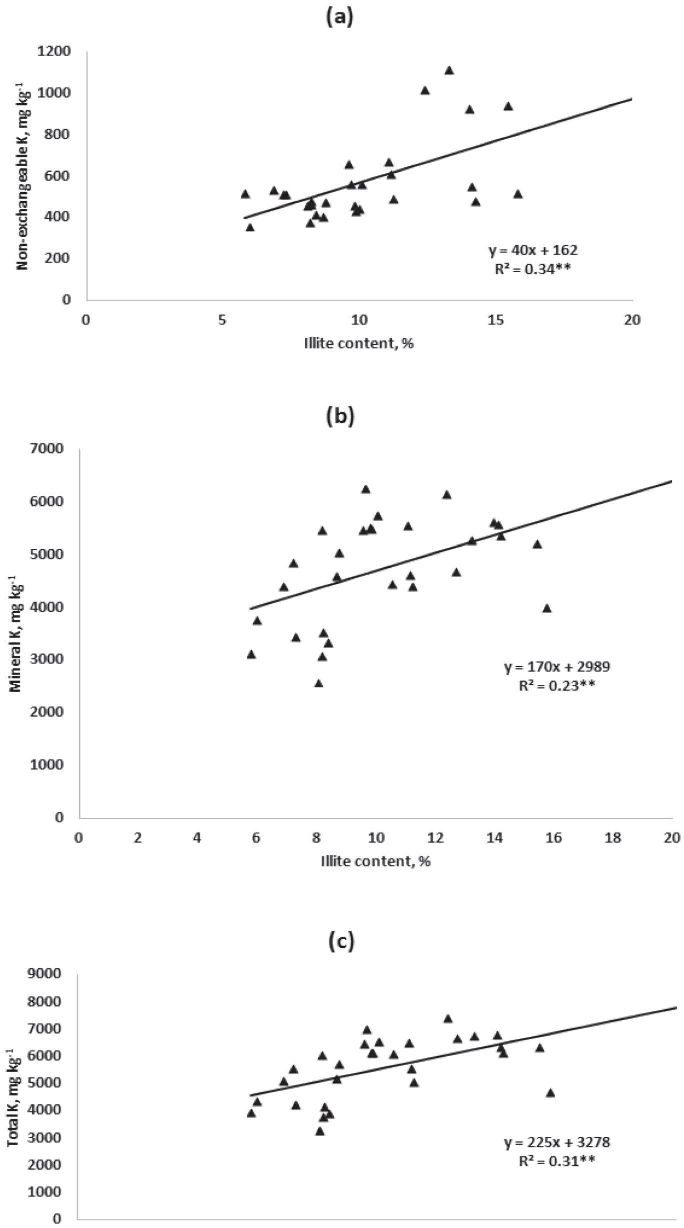

Figure 3 Relationships between illite content and non-exchangeable K (a), mineral K (b) and total K (c) for all soil samples

CONCLUSIONS

Paddy soils had lower contents of soluble, exchangeable and non-exchangeable K due to the K leaching by irrigation water and removal by plant uptake. On the other hand, mineral and total K in paddy soils was increased due to the addition of clay particles (containing K) suspended in irrigation water. Generally, more than 86% of total K was non-available (mineral K form) in paddy soils; while this value was 81% for non-paddy soils. Significant relationships were found between different forms of K and some soil properties like clay, CEC, sand, pH and OC. Mineralogical study indicated that although paddy and non-paddy soils differed in clay mineralogy composition (dominance of smectite in paddy soils vs. palygorskite and chlorite in non-paddy soils), the contents of non-exchangeable, mineral and total K were significantly correlated with illite content in the clay fraction, regardless of land use and soil depth. It is concluded that rice cultivation affects some soil properties and K status of soils and this should be considered for K management of paddy soils. Also, it is concluded that rice cultivation and submerging decreased more available forms of K (due to the removal of K ions by plant roots and leaching with irrigation water) and increased non available K (due to the addition of clay particles suspended in irrigation water) and this should be considered for K fertilizers recommendation in paddy cultivation systems.

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