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Potassium Behavior in Some Iranian Soils of Khuzestan Province Planted with Sugarcane

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Effects of potassium (K) fertilization, cropping history, and soil mineralogy on K fixation and availability were investigated in three sugarcane development projects. Hence, water-soluble, exchangeable, nonexchangeable, and available K (sum of water-soluble and exchangeable) was evaluated in the three projects including Haft-Tapeh (H), Karun (Ka), and Sugarcane Development Project (T) with 41, 26, and 8 years of sugarcane plantation, respectively, in the Iranian soils of Khuzestan province. According to the results, K fixation ranged from 17.74 to 129.15 mg kg^{-1} *and with increasing K levels, its amounts and percentage* ($P = 0.01$) *increased. With less than 30 years of plantation, there were not any differences in different plantation histories with regard to K fixation and availability. Evaluation of K dynamic based on long-term experiments can effectively contribute to the determination of appropriate rates of K fertilization for sugarcane production.*

Keywords K fixation, plantation history, soil properties, sugarcane (*Saccharum officinalis* L.)

Introduction

Sugarcane (*Saccharum officinalis* L.) is one of the most important industrial crop plants, widely planted in different parts of the world, including Iran. The main objectives of planting sugarcane are cane production and sugar extraction. Potassium (K) is one of the main nutrients necessary for sugarcane production at high amounts. Hence, its deficiency can very much affect plant performance and production. Compared with the other nutrients, K behaves differently, as it is found in soluble, exchangeable, nonexchangeable, and structural (crystallized) forms (Martin and Sparks 1985; Moody and Bell 2006) in the soil. Hence, if K behavior and the related effective parameters in the soil are evaluated, it can be useful for the development of appropriate K fertilization strategies (Ashkevari, Hossein Zadeh, and Miransari 2010, 2011).

The equilibrium and synthetic reactions among different forms of K determine soil K availability (Malavolta 1985). The main K source for crop use is the exchangeable K, which is in dynamic equilibrium with soluble K. Structural and nonextractable K are the

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nonexchangeable forms of K, usually trapped in the interspacing of mineral clay layers, which may become available for plant use after a long time. Accordingly, K fixation is defined as the adsorption of K by 2:1 clay minerals, especially illite and vermiculite (Barre et al. 2007).

If agricultural soils are not fertilized with K, soil K is depleted as a result of continuous cropping. With intensive crop planting, soil K is decreased to the levels less than sufficient, and even if K is fertilized, the plant will not be responsive at least for some time. It is because a part of fertilized K (soluble K) is adsorbed in the clay's interspacing layers, in places where the nonextractable K is depleted. Subsequently, and as a result of layer blockage, K becomes unavailable (Moody and Bell 2006). Parameters such as clay type and percentage, soil pH, amounts of calcium carbonate and iron and aluminum hydroxides, soil drying and wetting cycle, organic matter, and cropping history can affect K fixation in the soil (Malavolta 1985; Kwong and Ramasawmy-Chellen 2006).

Although with increasing K concentration, the amounts of nonextractable K increases. At greater K amounts the fixation percentage decreases. According to Arifin, Perkins, and Tan (1973), the Langmuir isothermal adsorption equation can be used for the explanation of soluble and nonextractable K behavior, where high rate of K is initially fixed. With increasing K amount, the rate of fixation decreases. Long-term cropping of plants, with high K demand, in unfertilized soils, results in the release and depletion of soil K from the clay's interspacing layer and hence mineral destruction. Ghorayshi (1988) indicated that in agricultural soils, K fertilization both supplies plant requirements and stabilizes mineral structure.

Several researchers have evaluated the effects of cropping history on K fixation and found significant correlations. In a research work on two different alluvial soils with similar physical and chemical properties but different cropping histories, greater amounts of K were fixed in soils with a longer cropping history at different K fertilizations ($P = 0.01$) (Sahu and Gupta 1987). Shinivasa Rao and Khera (1995) evaluated the effects of different rates of K fertilization on the K fixation and exchangeability in two different soils, soil A (with a little cropping history and with 60.8 and 20% of illite and clay, respectively) and soil B (with long cropping history and 34 and 9.7% of illite and clay, respectively). They found that exchangeable K increased at a greater rate in soil A in all K treatments, relative to soil B. They also indicated that with the addition of 20–200 mg kg^{-1} K to the soil after 2 months of incubation, the maximum K fixation in soil A was 39–42% and in soil B 74–82% of the original amount. Hosseinifard, Khademi, and Kalbasi (2010) indicated that parameters including the amounts of K absorbed by plant, plant age, and the initial amounts of exchangeable K are among the most important factors affecting the release of K from K clay minerals.

In a vertisol, after 10 years of intensified corn cropping in unfertilized soils, on average, soluble, exchangeable, nonexchangeable, structural, and total K were decreased to 82.5, 80.8, 48.7, 9.6, and 14.7%, respectively (Rao, Khera, and Rao 1994). As previously mentioned, K is among the most important macronutrients for the growth of different crop plants, including sugarcane. Hence, evaluation of its behavior in the soil can very much contribute to the proper determination of fertilizer recommendations. In this research work, we evaluated K behavior in the soil in some of the sugarcane fields with different cropping histories. Hence, the objectives were to evaluate (1) the status of different forms of K in the soil and (2) effects of K fertilization, cropping history, and soil mineralogy on K fixation and availability.

Materials and Methods

Soil Specifications and Properties

Seventy soil samples were collected from the soils depths of 0–30 and 30–60 cm, from three different sugarcane developing projects including Haft-Tapeh (Fluventic Haplustepts with 41 years of cropping history, H), Karun (Fluventic Haplustepts with 26 years of cropping history, Ka), and Sugarcane Developing Project (Fluventic Haplustepts and Typic haplosalids with 8 years of cropping history, T), located in the Iranian province of Khuzestan. Soils samples were selected with high variability in soil texture, available K, and cropping history from the fields, which had not been previously fertilized.

Soil samples were air dried, crushed, and passed through a 2-mm sieve and kept in storage containers. Soil physical and chemical properties were determined: soil texture using the hydrometer method (Sheldrick and Wang 1993); soil saturation percentage, soil pH, and electrical conductivity (EC) using pH meter and conductivity meter, respectively (Rhoades 1982); calcium carbonate (Nelson 1982); soil organic carbon (C) using the wet oxidation method (Nelson and Sommers 1982); cation exchange capacity (Bower, Reitemeier, and Fireman 1952); and water-soluble K in the saturated extract, ammonium acetate (NH_4OAc) (exchangeable) K, and nitric acid (HNO_3) (nonexchangeable) K (Knudsen, Peterson, and Pratt 1982). Water-soluble K was measured for 2 g of soil, shaken with 20 mL distilled water for 1 h, using a flamephotometer. Exchangeable K was measured using 5 g air-dried soil shaken with 50 mL of 1 M NH_4OAc for 30 min. Nitric acid–extractable K was determined using 0.5 g soil treated with 25 mL 1 M HNO_3 and digested (boiled) for 15 min using heating block at 150 °C. Nonexchangeable K was defined by subtracting water-soluble K and exchangeable K from HNO_3-extractable K (Hosseinifard, Khademi, and Kalbasi 2010). Available K, which is the sum of water-soluble and exchangeable K, was also calculated. Table 1 indicates soil physical and chemical properties for different experimental fields for the depths of 0–30 and 30–60 cm. The experimental soils are mostly silty clay, silty clay loam, and silty loam and are calcareous with alkaline pH and little organic matter.

Soil Mineralogical Properties

To identify the clay minerals, after removing the calcium carbonate, organic matter, and iron oxide, the collected clay part was saturated with magnesium (Mg) and K at room temperature. The clay parts were also saturated with Mg-glycerol and K and treated at 550 °C; using X-ray diffraction (XRD) the clay minerals were identified (Jackson 1975; Kittrick and Hope 1963).

Incubation Experiment

With regard to properties such as cation exchange capacity, clay type, exchangeable K with ammonium acetate, percentage of calcium carbonate, and cropping history, a total of 13 soil samples from the previously mentioned soil samples at 0–30 cm deep were selected to evaluate K fixation using the following method. Seventy grams of soil were placed on a plate and treated with K solutions with different concentrations (control, 150, 300, 600 mg kg^{-1} soil), which increased the sample moisture to a level slightly greater than field capacity. The samples were then incubated at 25–30 °C for 6 months using an incubator.

Table 1

Some of the soil physical and chemical properties for the different projects

		H				Ka				T			
		0–30 cm		30–60 cm		0–30 cm		30–60 cm		0–30 cm		30–60 cm	
Property	Unit	A	R	A	R	A	R	A	R	A	R	A	R
CH	year	33.1	27.0–41.0	33.1	27.0–41.0	21.8	17.0–26.0	21.8	17.0–26.0	6.8	5.0–8.0	6.8	5.0–8.0
Clay	%	31.7	20.4–42.8	32.6	20.4–44.8	34.1	16.0–50.0	36.5	22.0–52.0	33.7	15.6–47.6	34.6	15.2–51.6
Silt	%	46.2	35.6–55.0	44.4	30.6–54.0	52.2	44.8–60.8	52.2	44.8–62.8	41.4	15.6–55.6	40.1	15.6–56.0
Sand	%	22.1	11.6–41.6	23.0	9.6–47.6	13.7	5.2–23.2	11.4	3.2–19.2	25.0	0.8–67.2	25.3	0.8–68.8
SP	%	47.5	37.8–52.5	49.1	36.4–58.7	51.3	38.4–59.7	55.3	43.1–65.8	50.9	39.5–62.4	49.5	32.5–63.3
CEC	Cmol$_c$ kg^{-1}	14.5	10.5–18.7	14.1	9.1–18.3	14.8	9.9–20.5	14.9	11.1–20.1	14.4	7.1–20.9	14.2	6.6–21.3
OM	%	0.9	0.7–1.2	0.6	0.5–0.8	1.1	0.6–2.1	0.9	0.6–1.3	0.9	0.4–1.7	0.9	0.3–1.4
pH	–	8.0	7.7–8.3	7.9	7.7–8.1	8.1	7.6–8.5	8.1	7.9–8.4	7.8	7.2–8.3	7.9	7.3–8.3
ECe	dS/m	0.9	0.6–1.3	1.0	0.5–2.0	1.1	0.6–2.8	1.0	0.6–2.6	3.6	1.9–5.5	3.0	1.4–6.5
CaCO$_3$	%	34.4	31.5–38.1	34.3	29.9–40.2	39.4	31.9–44.8	38.4	35.7–40.9	39.9	31.8–45.6	39.8	31.3–46.3

Notes. H, Haft-Tapeh; Ka, Karun; T, sugarcane development project; A, average; R, range; CH, cropping history; SP, saturation percentage; CEC, cation exchange capacity; OM, organic matter; and EC, electrical conductivity.

During incubation, the samples were air dried and were then remoisturized using distilled water. The wet/dry cycle was repeated two to three times during the incubation period. Potassium fixation capacity was determined using the following equation:

$$K_F = (K_{av} + K_a) - K_t$$

where K_F is the amount of nonextractable K (mg kg^{-1}), K_{av} is available K (mg kg^{-1}), K_a is the fertilized K, and K_t is the available K (mg kg^{-1}) after the favorable period. Water samples were collected from the water canals in each field to determine the amounts of K in the irrigation water using flamephotometer.

Experimental Design and Statistical Analyses

The experiment was a factorial with four K concentrations (control, 150, 300, 600 mg kg^{-1} soil) and different cropping histories on the basis of a completely randomized design with three replicates. Data were subjected to analysis of variance using SAS (SAS Inc. 1988). Comparisons of means were made using Duncan's multivariate test (Steel and Torrie 1980).

Results

Soil K Analyses for Different Fields

The greatest amounts of soluble K for both depths were found in the T fields, relative to the other fields. Similarly, for exchangeable K, the T and K fields resulted in greater amounts of K relative to H fields. The maximum amounts for both depths were related to the T fields, followed by Ka fields. For nonexchangeable K at the 0 to 30 cm depth, the greatest amount was determined at Ka sites, while for the 30 to 60 cm depth, the amounts were similar for all sites (Figure 1).

The concentration of exchangeable K for the depth of 0–30 cm ranged between 42.5 and 165.33 with the average of 91.61 mg kg^{-1} and for the depth of 30–60 cm ranged from 40.0 to 134.7 mg kg^{-1}. Apparently, such amounts are about the sufficient level or less. Soluble K (intensity factor) for the depth of 0–30 cm ranged from 0.6 to 17.2 mg L^{-1} with the average of 5.3 mg L^{-1} and for the depth of 30–60 cm was between 1.2 to 12.8 mg L^{-1} with the average of 3.8 mg L^{-1} (data not shown).

Effects of Incubation Time on K Fixation and Availability

The longer incubation time enhanced K availability (sum of soluble and exchangeable K) as greater amounts of fertilized K became available after 6 months of incubation, compared with 3 months of incubation. After 3 months of incubation, K availability ranged from the minimum of 60% in H fields to the maximum of 81.7% in T fields. Comparison of different fields indicated that with increasing K fertilization, the percentage of available K decreased. However, for the 3 months of incubation, the differences in available K, as affected by different K fertilization rates, were less relative to those from 6 months of incubation (Figure 2). It is obvious that even 6 months after incubation, and at different K concentrations, about 70% of the fertilized K was still available for plant use. According to the results, there are not any significant differences between the soils of T and Ka fields

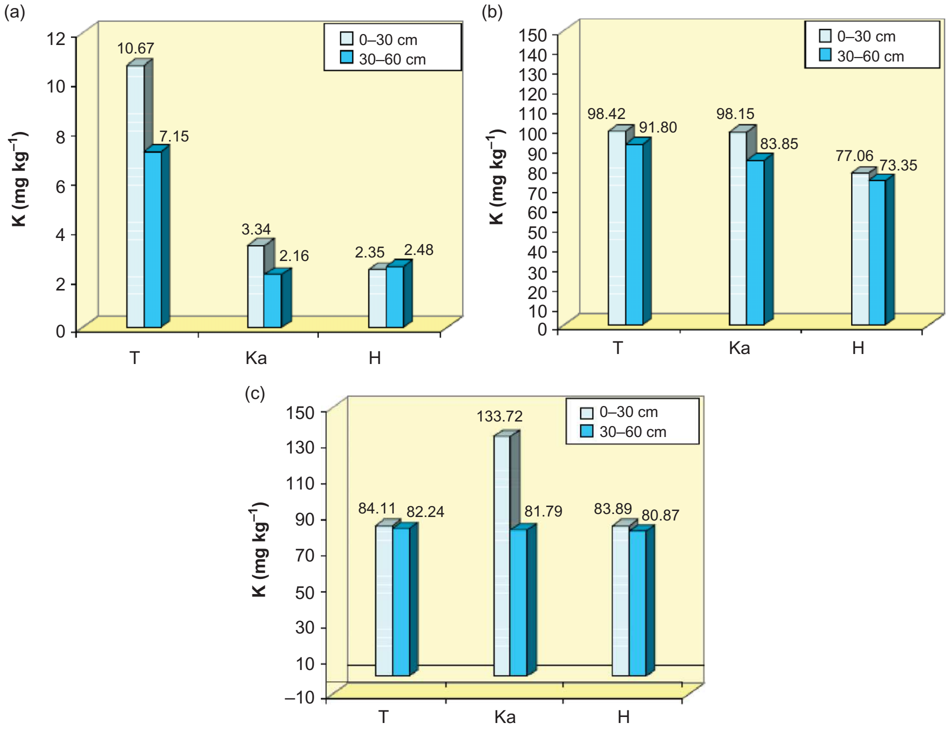

Figure 1. Mean comparisons (mg kg^{-1}) of (a) soluble K, (b) exchangeable K, and (c) nonexchangeable K in different experimental fields including T, sugarcane developing project; Ka, Karun; and H, Haft Tapeh (color figure available online).

regarding the increase in available K; however, the differences between H and the other fields are significant ($P = 0.01$).

Potassium Fixation

Tables 2 and 3 present the mineralogical, physical, and chemical properties of the experimental soils with regard to their K fixation. According to Table 2, the dominant minerals include chlorite, smectite, illite, and clay minerals, and their variation is dependent on the climate properties. The averages of K fixation (for the treatment of 600 mg kg^{-1} and after 6 months of incubation) in the fields of H, Ka, and T were equal to 206.4, 179.7, and 189.0 mg kg^{-1}, respectively. If soil bulk density is assumed at 1.5 g cm^{-3}, the amounts of nonextractable K in these soils in the depths of 0–30 cm are equal to 928.7, 808.7, and 850.4 kg per hectare (equal to 1896.9, 1804.1, and 2071 kg potassium sulfate per hectare).

Comparison of the two depths indicates that the amount of organic matter as well as soluble, exchangeable, and nonexchangeable K in the 0 to 30 cm depth is greater than in the 30 to 60 cm depth ($P = 0.01$). For the 0 to 30 cm depth, 40% of the soils in this experiment contain less than 90 mg kg^{-1} available K, 43.0% contain 90–120 mg kg^{-1}, and just 17.1% contain more than 120 mg kg^{-1}. For the depth of 30–60 cm, 62.9% of soils contain less than 90 mg kg^{-1} available K, 22.9% contain 90–120 mg kg^{-1}, and only 14.3% contain more than 120 mg kg^{-1} (Table 3).

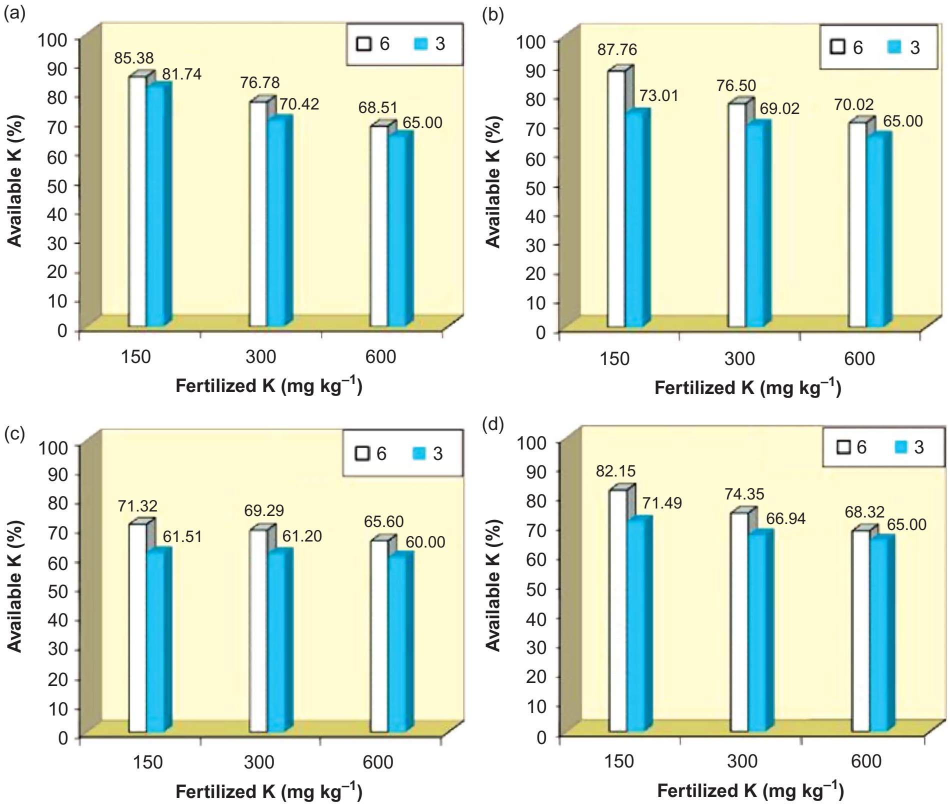

Figure 2. Available K as affected by different K fertilization, after 3 and 6 months of incubation, in (a) developing sugarcane project, (b) Karun, (c) Haft Tapeh, and (d) the average of the three fields (color figure available online).

Tables 4 and 5 represent the analyses of variance for K fixation at different K levels after 3 and 6 months of incubation and the mean comparisons using Duncan's multivariate test for the average of nonextractable K at different K levels. Hence, there was not any K fixation in the control samples, indicating that the wetting and drying cycles resulted in the release of K from the nonexchangeable sites according to the concentration gradient ($P = 0.01$).

The results indicated that there is significant correlation between the amounts of nonextractable K and the percentage of fertilized K, which turned into available K, with the cropping history ($P = 0.01$). According to the mean comparisons, there are not any significant differences between different cropping histories regarding K fixation before the time period of 30 years; however, for longer times, K fixation and the percentage of fertilized K that turned into available K increased (Table 5).

Discussion

With regard to the significance of K for sugarcane production, in this research work the effects of different parameters including cropping histories, clay mineralogy, and K fertilization on the behavior of different soil K forms and sugarcane production were evaluated. Accordingly, K fractionation including water-soluble, exchangeable, nonexchangeable,

Table 2
Soil mineralogical status

Soil sample	Field	Illite	Vermiculite	Chlorite	Smectite	Layered minerals	Kaolinite
1	T	+++	−	++++	+++++	++	−
2	T	+++	−	++++	+++++	++	+
3	T	+++	−	+++++	++++	++	−+
4	Ka	+++	−+	++++	+++++	++	+
5	Ka	++++	−+	+++++	+++	++	+
6	Ka	++++	−+	+++++	+++	++	+
7	Ka	+++	−+	+++++	++++	++	−
8	Ka	+++	−+	++++	+++++	++	+
9	Ka	+++	−+	+++++	++++	++	−
10	H	++++	−	+++++	+++	++	+
11	H	+++	−	++++	+++++	++	+
13	H	+++	−	++++	+++++	++	−

H, Haft-Tapeh; Ka, Karun; and T, sugarcane development project. "+" indicates that the mineral is available in the soil and "−" indicates that the mineral is not available in the soil. The higher number of "+" indicates the higher abundance of mineral in the soil.

and available K was determined. Such results reflect the effects of different cropping history on K dynamic in the soil. In addition, the incubation experiment also indicated that how K dynamic in a certain time (3 and 6 months) may be affected by K fertilization and wetting and drying cycles.

The T and Ka sites resulted in the greatest amounts of soluble and exchangeable K, indicating that their buffering capacity is greater than the H fields in regards to supplying necessary K for sugarcane production. This can be attributed to the greater amounts of clay (Table 1), including the presence of 2:1 mineral clays, illite, chlorite, and smectite (montmorilonite) (Table 2). It should be mentioned that K absorption on the clay minerals affects both K availability and mineral quantity, meaning that K absorption can also modify the combination of mineral structures in the soil (Barre et al. 2008).

For the H fields, greater amounts of K fertilization will be necessary to attain comparable amounts of sugarcane yield relative to the other fields. There were not any significant differences between the fields with the cropping histories less than 30 years regarding their K supply; the fields have been able to provide K for a long time while not fertilized. However, especially for the H fields with regard to the soil buffering capacity, the soil must be fertilized on a regular basis to achieve high yield production for a long time (Simonsson et al. 2007).

Exchangeable and nonexchangeable K sources are the most important source of K for plant use, which can also control the amounts of soluble K (Hinsinger 2002). However, nonexchangeable and structural K may become available for plant use after a long time through structural changes in the soil, for example, by the wetting/drying cycle or the weathering processes. Hence, consideration of soil K dynamic for about half a century can be very useful to precisely evaluate K behavior in the soil. Such behavior is affected by different parameters, including K fertilization, soil mineralogy, and wetting and drying cycle.

The greater K fertilization efficiency in the longer time (of incubation) indicates that longer time is mandatory for different soil phases, including the soluble and exchangeable

Table 3

Physicochemical properties of the selected soil samples, subjected to the K fertilization

Soil sample	CH (year)	Clay (%)	Silt (%)	Sand (%)	Texture	CEC ($Cmol_C$ kg^{-1})	Ca-CO_3 (%)	SP (%)	OM (%)	pH	EC (dS m^{-1})	Sol.K (mgL^{-1})	Exch. K (Mg kg^{-1})	Available K (Mg kg^{-1})	Nonexch. K (Mg kg^{-1})
9	7	17.2	23.2	59.6	S.L	7.2	40.1	41.1	0.4	7.6	4.6	13.7	68.3	74.0	148.0
15	7	37.6	53.6	8.8	SI.C.L	17.0	36.3	54.1	1.3	8.0	4.6	5.7	87.6	90.7	119.3
21	8	47.6	47.6	4.8	SI.C	20.7	34.6	62.4	1.7	8.3	3.2	10.5	137.4	144.0	47.5
33	17	16	60.8	23.2	SI.L	10.0	42.3	38.4	0.6	8.2	9.0	2.9	44.3	45.4	86.2
27	20	39.6	44.8	15.6	SI.C	16.0	35.0	52.6	0.9	8.5	1.0	4.0	151.7	153.8	94.2
35	17	50	44.8	5.2	SI.C	20.6	41.0	59.7	2.1	8.3	0.8	7.2	168.2	172.6	104.4
31	25	28	54.8	17.2	SI.C.L	11.6	44.4	56.8	9.0	8.2	0.9	2.4	73.6	74.9	48.1
43	26	35.6	55.2	9.2	SI.C.L	16.3	36.7	54.8	1.3	8.1	1.5	2.4	92.4	93.7	104.3
29	26	46	46.8	7.2	SI.C	16.1	36.3	58.8	1.4	8.5	0.8	1.9	121.2	122.3	133.2
53	41	20.4	55.0	24.6	SI.L	11.8	37.7	47.1	0.9	7.8	1.2	1.9	55.3	56.2	45.8
71	29	24.8	35.6	39.6	L	10.8	31.6	40.5	0.7	7.7	0.8	3.7	54.7	56.2	110.3
51	41	32.4	53.0	14.6	SI.C.L	15.5	34.5	46.7	1.1	8.0	1.0	2.8	71.7	73.0	110.0
61	30	40.8	47.6	11.6	SI.C	17.4	33.2	50.6	1.1	7.9	0.6	1.9	94.7	95.6	162.4

Notes. CH, cropping history; CEC, cation exchange capacity; SP, saturation percentage; OM, organic matter; EC, electrical conductivity; sol. K, soluble K; exch. K, exchangeable K; and nonexch. K, nonexchangeable K.

Table 4

Analysis of variance, for the effects of cropping history and K fertilization on K fixation at 3 and 6 months after incubation

		Mean of squares	
SV	df	K fixation, after 3 months	K fixation, after 6 months
CH	3	872.8^{**}	2191.7^{**}
K	3	44480.2^{**}	21851.3^{**}
K × CH	9	$109.9^{\text{n.s.}}$	$633.1^{\text{n.s.}}$
ER	16	30.0	74.4
SE	124	173.2	389.6

Notes. CH, cropping history; K, K fertilization; ER, experimental error; SE, sampling error.

**Significant at $P = 0.01$.

N.s., not significant.

Table 5

Mean comparison of K fixation (mg kg^{-1}) and availability (kg ha^{-1}) at 3 and 6 months after incubation, as affected by K fertilization and cropping history, using Duncan's multivariate test

K (mg kg^{-1})	N	K3	K6
K fixation and K fertilization			
0	39	−16.6d	−19.2d
150	39	26.8c	42.8c
300	39	77.0b	99.2b
600	39	190.1a	131.9a
K fixation and cropping history			
10>	36	66.1b	53.8b
10–20	36	62.3b	55.2b
20–30	36	60.7b	51.9b
>30	48	83.4a	86.3a
K availability and cropping history			
10>	36	196.4a	208.7a
10–20	36	200.2a	207.3a
20–30	36	201.8a	210.6a
>30	48	179.1b	176.3b

phases, to reach the equilibrium. Hence, this must be taken into account when planning K fertilization for sugarcane. In other words, to increase K efficiency for sugarcane use, K fertilization must be conducted a few months before cropping sugarcane, which is also influenced by clay mineralogy.

Gawander et al. (2002) evaluated the different forms of K under sugarcane production and measured soluble K ranging from 12.09 to 61.01 mg L^{-1} with an average of 23.4

mg L^{-1}. According to Meyer and Wood (1985), the least sufficient amount of exchangeable K for sugarcane production is 113 and 225 mg kg^{-1} for soils with light–medium and heavy textures, respectively. Accordingly, with respect to the soil texture, the results of this research work (Table 3) indicate that for all fields, K fertilization is necessary as the fields have been under sugarcane production for a long time. According to Twyford and Wright (1965), the least sufficient level of exchangeable K for sugarcane with yield production of 112 ton/ha is equal to 249 to 300 mg kg^{-1}, indicating that the level of exchangeable K in Haft-Tapeh is not adequate.

Because little exchangeable K was obtained and soluble K is a function of exchangeable K, the little soluble K in these fields is expected. In addition, calcite presence in the soil (Table 1) can make the reversible exchange of exchangeable and soluble K likely (Simonsson, Hillier, and Öborn 2009). Comparison of the two depths indicates that the amount of organic matter and soluble, exchangeable, and nonexchangeable K in the 0- to 30-cm depth is greater than in the 30 to 60 cm depth ($P = 0.01$). This is because a large part of absorbed K by sugarcane is translocated to the plant shoot and leaf, which are eventually turned into soil organic matter in the upper soil.

Tables 2 and 3 present the mineralogical, physical, and chemical properties of the experimental soils with regard to K fixation. According to Table 2, the dominant minerals include chlorite, smectite, illite, and clay minerals and their variation is dependent on the climate properties. Jafari, Bagher-Nejad, and Charm (2005) evaluated K fixation in the soils under sugarcane in the Haft-Tapeh region and the nearby unplanted soils of Khuzestan, Iran, and indicated that expansible clays have been formed in the soils. They attributed such phenomena to the long cultivation and irrigation.

Both K fertilization and cropping histories significantly affected K fixation (Tables 4 and 5) at different incubation times, indicating that such parameters must be taken into account when planning K fertilization strategies. Another interesting point about the results of this experiment is the indication of K fixation percentage at a certain time, which can be very useful for the determination of appropriate rates of K fertilization.

The tested soils in this research work do not have a high capacity for K fixation, which can be very favorable for sugarcane production as it increases the efficiency of K fertilization. However, it should be mentioned that for a cropping history of more than 30 years the soils indicated more fixing capacity and less K availability (Table 5). This may be attributed to the high depletion of K from the soil over a long time. The chemical structural changes that may have been created during the cropping period as a result of the wetting and drying cycle also indicated this.

Johnston and Mitchell (1974) indicated that the initial exchangeable K is a linear function of nonexchangeable K release. Drying a soil, with little available K, results in the release of K from the nonexchangeable sites (Steenkamp, Theron, and de Bruyn 1989). Similar results were found for the Haft-Tapeh region, as the increased K concentration enhanced the amount and percentage of K fixation ($P = 0.01$) (Jafari, Bagher-Nejad, and Charm 2005). However, several researchers have indicated that the general trend of isothermal fixation is like the following: A high percentage of fertilized K is initially fixed and then with increased K the rate of K fixation decreases. Sometime the trend is ultimately linear. It should be mentioned that such results are not related to long-term experiments but to short-term experiments of a few days (Arfin, Perkins, and Tan 1973; Badraoui and Bloom 1989).

Potassium fixation increases with the movement of K ions from the mineral edges and surfaces toward the internal parts of the mineral. Since this process is not fast, the rate of K fixation increases with time with respect to the specific K sites and the percentage of soil saturated K. In other words, with adding K to a depleted soil, K ions are immediately placed on the mineral edges and surfaces. This inhibits the fast entrance of K to the internal parts of mineral. A 6-month period for the establishment of equilibrium is necessary (Karim and Malek 1956). It should be mentioned that one of the main objectives of performing laboratory experiments is to make the conditions more similar to field conditions. Hence, the incubation experiment in this research was conducted over a relatively long time.

Figure 2 indicates the increase in available K percentage under different concentrations and two different times (3 and 6 months) for different fields. It is obvious that even 6 months after incubation, and at different K concentrations, about 70% of the fertilized K is still available. Similar results have been found by Jafari, Bagher-Nejad, and Charm (2005) for the Haft-Tapeh fields. Hence, with the depletion of K, especially in soils with long cropping histories, just a little part of fertilized K will not be in the reach of plant by fixation in the interspatial layers. This indicates that if K fertilizer is supplied to such soils, a significant part of it remains available for the plant use. The results indicated that there is significant correlation between the amounts of nonextractable K and the percentage of fertilized K, which turns into available K, with the cropping history ($P = 0.01$). These results are in agreement with the results by Shinivasa Rao and Khera (1995).

The following details are necessary with regard to the water properties and the previously mentioned results. Water analysis indicated that K concentration in the irrigation water, depending on its source (e.g., Daz and Karun Rivers), on average is about 2.5 mg L^{-1} (Jafari, Bagher-Nejad, and Charm 2005; Barani-Motlagh and Savaghebi 2005). The amount of water used during the growing season for each hectare is 30,000 m^3 per year (Jafari, Bagher-Nejad, and Charm 2005) indicating that about 75 kg K ha^{-1} (equal to 170 kg potassium sulfate) is supplied by the irrigation water. In addition, the accumulation of 50% of absorbed K in the plant is a suitable source of K for the following crop.

Furthermore, according to the results, since the soil had been sufficient in K (mineralogical analysis) before plantation and had a high K buffering capacity (Bostani and Savaghebi 2006), the soil had been able to provide the adequate amount of K for a relatively long time; no fertilization had been necessary. Hence, the irrigation water and the plant residues in the initial years resulted in the little decrease in the ratio of available K necessary for plant growth with time. This indicates that K harvest by plant for almost 30 years did not result in the significant depletion of K from the nonexchangeable sites. However, after this time, the available K decreased to a level, less than sufficient, resulting in the turning of nonexchangeable K into available K and hence the onset of K depletion.

Conclusion

Sugarcane absorbs greater amounts of K, relative to the other nutrients. Sugarcane harvest, under unfertilized conditions, results in the depletion of soil K over a long time. According to the results, the level of available K, especially, for the Haft-Tapeh field, is less than the sufficient level. With increasing K concentration, both the amounts and the percentage of K fixation increased ($P = 0.01$). About 30% of the fertilized K was fixed after 6 months of incubation and 70% remained available for plant use (Simonsson, Hillier, and Öborn 2009). In the control treatment, the wetting and drying cycle resulted in the release of K and increased the available K (Simonsson, Hillier, and Öborn 2007). According to the results, the amounts of nonextractable K and the increase in available K in soils with the cropping history over 30 years were significantly greater than those of the other soils. The details indicated in this research work can contribute to the appropriate determination of K fertilization for sugarcane production. In brief, we may conclude that soil K dynamic over a long time is affected by different parameters including (1) soil properties such as soil clay minerals, soil buffering capacity, and organic matter, (2) plant properties, (3) fertilization method, (4) wetting and drying cycles, (5) cropping history, and (6) climate.

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