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Effects of potassium and iron on macro element uptake of maize

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Abstract

The current research was conducted to determine the effects of different potassium (K) and iron (Fe) rates on the growth and some macro nutrient uptake of maize. For this purpose, five K (1, 2, 4, 6 and 8 mM) and four Fe (30, 60, 90 and 120 µM) doses were applied to maize (*Zea Mays* L. cv. BSC 6661) plants in a re-circulated hydroponic system. Increasing K and Fe levels had positive effects on dry weight of the maize leaves and roots. The total Fe and active Fe concentrations and their uptake increased with the increasing levels of Fe and K, but these amounts decreased with the highest K dose. The addition of increasing levels of K decreased the P, Mg, and Ca concentrations in both leaves and roots of maize. Although the lowest dose of K and Fe has positive effects, the elevated K and Fe doses decreased their uptake in both roots and leaves.

Key words: active iron, antagonism, hydroponic system, interaction.

Introduction

Balanced nutrition of the plants is one of the main factors that affects the yield and quality of the plants. Potassium (K) is regarded as one of the major nutrient element which affects the yield and quality of grain and fruits. This nutrient plays an essential role in plant growth and metabolism (Ruiz, Romero, 2002). It activates enzymes, serves as an osmoticum to maintain tissue turgor pressure, regulates the opening and closing of stomata, and balances the charge of anions (Marchner, 1995; Mengel, 2007).

Another essential nutrient is iron (Fe), the lack of which causes chlorosis and is responsible for significant decreases in yield and quality of plants. Although most soils contain adequate total iron, amounts that are available to plants might be inadequate dependent on various soil factors such as very high or low soil temperature, high humidity, poor soil aeration and compaction, high pH, HCO_3^- and $CaCO_3$ contents. Besides the bad physical properties of the soils Fe chlorosis is also related with PO_4^- and NO_3^- anions and other heavy metal concentrations such as Zn, Cu, Mn, Co, Ni and Cd (Başar, 2000; Lucena, 2000).

Excess applications of K or increasing amounts of K release under suitable soil conditions can inhibit the Fe uptake and may affect the degree of Fe chlorosis. Urrestarazu et al. (1994) also pointed out that plants take K much more than Fe and excess amounts of K inhibit uptake and translocation of Fe in plants and lead to Fe deficiency. Some recent studies showed that when the chlorosis symptoms occurred, K contents of the plant were found high at these chlorotic plant samples (Torres et al., 2006; Çelik, Katkat, 2007). As shown in Fe, K uptake and utilization also interact with the availability and uptake of other macronutrients. The interactions can either enhance or reduce nutrient uptake and utilization.

This study was aimed to determine the interactions between Fe, K and other macronutrients and examine the effects of high amounts on their uptake in to the roots and leaves of maize plant.

Materials and methods

Nutrient solution experiment. Maize (*Zea mays* L. cv. BSC 6661) seeds were germinated in a perlite medium that was moistened with half strength nutrient solution containing the following (in mM): Ca $(NO_3)_2$ – 2, K_2SO_4 – 0.75, $MgSO_4$ – 0.65, KH_2PO_4 – 0.5 and (in µM): KCl – 25, H_3BO_3 – 10, FeEDDHA – 10, $MnSO_4$ – 1, $CuSO_4$ – 0.5, $ZnSO_4$ – 0.5, $(NH_4)Mo_7O_{24}$ – 0.05 (Çelik et al., 2006). The maize plants were transferred into re-circulated hydroponic systems after ten days of preculture. A hydroponic system consists of a solution tank that contains a 50-L volume of nutrient solution, a pump and three channels parallel to each other. Each channel contained four plants. Twenty different nutrient solutions composed of five K doses (1, 2, 4, 6 and 8 mM) and four Fe doses (30, 60, 90 and 120 µM) were administered to the plants in twenty hydroponic systems during the vegetation period. The nutrient solutions pH ranged between 6.93–8.06 and E.C. values ranged between 982–1407µS cm^{-1} due to their nutrient contents. Information about the composition of the nutrient solutions is given in Table 1. The nutrient solutions were renewed every 4–5 days.

Table 1. Nutrient elements, concentrations and their resources used in the experiment

Nutrient elements	Concentrations in the solutions	Nutrient resources
	mM	
N	6	KNO_3, $Ca(NO_3)_2$
P	1	KH_2PO_4, K_2HPO_4
K	1–2–4–6–8	KH_2PO_4, K_2HPO_4, KNO_3, K_2SO_4
Ca	3	$Ca(NO_3)_2$, $CaSO_4 2H_2O$, $Ca(OH)_2$
Mg	2	$MgSO_4 7H_2O$, MgO
S	2	K_2SO_4, $MgSO_4 7H_2O$, $CaSO_4.2H_2O$
	µM	
Fe	30–60–90–120	FeEDDHA % 6 Fe
B	10	H_3BO_3
Zn	2	$ZnSO_4 7H_2O$
Mn	2	$MnSO_4 4H_2O$
Cu	1	$CuSO_4 5H_2O$
Na	0.1	NaCl
Cl	0.1	NaCl
Mo	0.05	$(NH_4)_6Mo_7O_{24}.4H_2O$

Maize plants were grown for 41 days, which was long enough for the influence of the effects of the treatments. The aerial parts of the plants were harvested on 41st day. The leaf and root samples were immediately transported to the laboratory in closed polyethylene bags. For the evaluation of nutrient uptake of the plants, the plant materials were washed once in tap water and then twice with deionised water. After washing, the plant material was dried in a forced air oven at +70°C for 72 hours; and ground with a laboratory mill. The ground plant samples were digested using a mixture of 2 ml of HNO_3 and 3 ml of H_2O_2 in a microwave oven (Berghof MWS 2) (Wu et al., 1997). The iron (Fe) content in the digest was determined by ICP-OES (Perkin Elmer Optima 2100 DV) (Isaac, Johnson, 1998). The K, Na, Ca amounts were determined by flame emission (Eppendorf Elex 6361) (Horneck, Hanson 1998); Mg – by atomic absorption spectrophotometry (Philips PU 9200x, Pye Unicam Ltd. GB) (Hanlon, 1998) and P – by vanadomolybdophosphoric method (Lott et al., 1956). Total N was determined by Buchi K-437/K-350 digestion/distillation unit (Bremmer, 1965). Active Fe^{++} contents were determined in the dry plant parts by incubating 24 h in 1 N HCl extraction solution (1:10) using the method of Oserkowsky (1933) that was modified by Llorente et al. (1976) and resultant amounts were measured by ICP-OES.

All of the analyses were conducted in triplicate. The mean values were compared using the LSD (Least Significant Differences) multiple range test, and simple correlations were measured with the computer program *Tarist*.

SPAD value measurements. A portable chlorophyll meter (SPAD-502, Minolta Camera Co., Japan) was used to measure the leaf chlorophyll content at 20, 27, 34 days after the transfer and at the harvest (Cordeiro et al., 1995). The upper most fully expanded leaf was selected from each plant to measure and record the SPAD values. Three SPAD readings were taken around the midpoint of each leaf. Twelve SPAD readings were averaged to give the mean SPAD value of each channel.

Results and discussion

According to the general appearance of the plant in the experiment, the development of the maize plants was poor at the time of the first dose of K and Fe. The plants were small and showed both K deficiency and Fe chlorosis symptoms. The increasing amounts of K and Fe further affected the development. The plants became taller and greener with the addition of increasing amounts of K and Fe than at the first doses. The potassium deficiency symptoms disappeared. The iron chlorosis symptoms were also fading due to the increasing amounts of Fe, but they did not completely vanish with the subsequent K doses. Numerous solution culture methods and pot experiments with K^+-free substrates have shown that plants do not grow without K. As soon as the potassium reserves of the seed are exhausted, the plants die (Mengel, 2007). According to the physical appearance of the plants in our research, neither the first dose of K, nor the application of additive Fe was sufficient for the healthy development of the maize plants and confirms the findings of Mengel (2007).

The effects of increasing amounts of K and Fe on the dry weight of maize leaves and the roots are shown in Tables 2 and 3. Increasing the K levels had positive effects on the dry weight of maize leaves and roots. The elevated amounts of Fe also affected this increase, but the application of the highest K and Fe doses decreased the growth due to the interactions between K, Fe and the other nutrients. While the highest dry weight amount in the leaves (145.46 g) was taken from the K3Fe4 application, increasing the K decreased the weight that was measured as 93.45 g at K5Fe4 application (Table 2). The dry weight of the maize roots was also positively affected by the application of K and Fe. Neither the highest dose of K nor the third and forth dose of Fe were enough to reach the maximum weight. The highest weight (40.74 g) was taken from the K4Fe4 application (Table 3). Elevated concentrations of K had positive effects on the plant growth, and various researchers (Cheema et al., 1999; Mahmood et al., 1999; Jabbar et al., 2009) have shown the direct effect of K on plant growth and development. In a pot experiment comprising graded doses of K and Fe, Sahu and Mitra (1992) reported that the dry matter yield of rice increased with increasing doses of K. However, they indicated that the excess amounts of K depressed the plant growth and yield.

Table 2. Effects of increasing amounts of potassium and iron on dry weight of maize leaves (g pot^{-1})

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
	Dry weight g pot^{-1}				
K1, 1 mM	16.79 b C	50.64 b B	81.70 b AB	86.49 c A	58.91 b
K2, 2 mM	30.89 b C	55.06 b BC	78.95 b B	121.18 ab A	71.52 b
K3, 4 mM	46.60 b C	95.53 a B	116.82 a AB	145.46 a A	101.08 a
K4, 6 mM	48.50 b C	93.40 a B	127.04 a A	143.67 a A	103.15 a
K5, 8 mM	83.10 a A	95.42 a A	83.77 b A	93.45 bc A	88.93 a
Means	45.16 D	78.01 C	97.66 B	118.05 A	
$Fe_{LSD<0.01}$: 14.754		$K_{LSD<0.01}$: 16.495		$Fe*K_{LSD<0.01}$: 32.991	

Notes. The differences between values indicated by different letters are significant. Capital letters indicate rows and small letters indicate columns.

Table 3. Effects of increasing amounts of potassium and iron on dry weight of maize roots (g pot^{-1})

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
	Dry weight g pot^{-1}				
K1, 1 mM	5.59 c B	11.75 b AB	19.86 c A	19.18 b A	14.10 b
K2, 2 mM	9.61 bc B	12.04 b B	24.85 bc A	30.24 a A	19.19 b
K3, 4 mM	15.77 b C	27.54 a B	32.14 ab AB	40.21 a A	28.91 a
K4, 6 mM	12.53 bc C	26.98 a B	38.82 a A	40.74 a A	29.77 a
K5, 8 mM	25.15 a B	29.05 a AB	29.02 b AB	35.65 a A	29.72 a
Means	13.73 C	21.47 B	28.94 A	33.20 A	
$Fe_{LSD<0.01}$: 4.901		$K_{LSD<0.01}$: 5.479		$Fe*K_{LSD<0.05}$: 8.188	

Note. Explanations under Table 2.

Visual chlorotic symptoms were also supported by the SPAD readings. Iron applications affected the SPAD readings positively. The SPAD values were increased due to the increasing amounts of Fe. The maize leaves with high concentrations of Fe had higher SPAD readings than those with a low concentration of Fe. While the SPAD value for treatment Fe1 was 8.43–12.67, this value was 30.27–35.47 for treatment Fe4. In addition to the Fe concentrations, the K doses also had a positive effect. The fourth dose of K had the highest SPAD values compared with those with low concentrations of potassium (K1, K2 and K3). Although there was a positive effect of increasing amounts of K, the highest dose (K5) lowered the SPAD values (Table 4).

Table 4. Effects of increasing amounts of potassium and iron on SPAD readings of maize leaves

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
	SPAD values				
K1, 1 mM	8.43 b C	18.60 c B	29.83 bc A	32.53 ab A	22.50 c
K2, 2 mM	9.53 ab C	19.20 bc B	31.57 b A	33.83 a A	23.53 c
K3, 4 mM	12.53 a C	24.27 ab B	31.43 b A	33.73 a A	25.49 b
K4, 6 mM	12.67 a C	25.50 a B	35.80 a A	35.47 a A	27.36 a
K5, 8 mM	11.43 ab C	21.97 bc B	27.53 c A	30.27 b A	22.80 c
Means	10.92 D	21.91 C	31.23 B	33.17 A	
$Fe_{LSD<0.01}$: 1.467		$K_{LSD<0.01}$: 1.640		$Fe*K_{LSD<0.01}$: 3.280	

Note. Explanations under Table 2.

Similar to the dry weight of both roots and leaves of maize and the SPAD values, the total Fe and the active Fe concentrations as well as their uptakes increased with the increasing levels of Fe and K, but the amounts decreased with the highest K dose, especially in the K5Fe4 application. Although the total and active Fe concentrations of the leaves were 47.31 mg kg^{-1} and 42.01 mg kg^{-1} in the K4Fe4 application, respectively, these values decreased to 44.71 mg kg^{-1} for total Fe and 29.01 mg kg^{-1} for active Fe with the K5Fe4 application (Table 5). Sahu and Mitra (1992) observed that although the uptake of K increased with increasing K doses, the ratio of Fe/K continued to decrease indicating that K has also an antagonistic effect on Fe uptake. Fe toxicity is also associated with K deficiency, especially in heavy soil (Tanaka et al., 1973) and can be ameliorated or eliminated by potassium fertiliser applications (Tanaka et al., 1973; Li et al., 2001; Çakmak, 2005). The ameliorating effects of K may be attributed to the antagonistic effect of K on Fe absorption and translocation into the shoots (Li et al., 2001). This situation clarifies the high contents of iron at K1 level in both leaves and roots of maize. The response mentioned above was much more evident at the roots. The concentration of Fe was found high in the roots. The highest total Fe concentration (1353.67 mg kg^{-1}) was measured with the K3Fe4 application and tended to decrease with increasing amounts of K. This value was measured as 1180.73 mg kg^{-1} with K4Fe4 and 896.03 mg kg^{-1} with K5Fe4 applications (Table 6). Mengel (1995) reported that chlorotic vines and peaches also had high Fe concentrations in the roots. In our research, the greatest concentrations of Fe in the roots confirm the findings of Mengel (1995). High amounts of Fe in roots are the evidence that Fe may accumulate in the roots. High concentrations of K affected the uptake of total and active Fe. The highest uptake (6.80 mg tdw^{-1}) for the total Fe and (6.02 mg tdw^{-1}) for the active Fe occurred with K4Fe4 application, these values decreased to 4.16 mg tdw^{-1} and to 2.73 mg tdw^{-1} respectively, with the K5Fe4 application (Table 7).

High concentrations of K also lowered the total Fe uptake in the roots. The highest uptake (53.88 mg tdw^{-1}) was with the K3Fe4 treatment, and it decreased to 48.48 mg tdw^{-1} with the K4Fe4 application and 32.35 mg tdw^{-1} with the K5Fe4 application (Table 8). Urrestarazu et al. (1994) also pointed out that plants absorb K much more than Fe and that excess amounts of K inhibit the uptake and translocation of Fe in plants, leading to Fe deficiency. Demiral and Köseoğlu (2005) reported that the application of increasing amounts of K lowered the Fe and Mn contents of the Galia melon from that of the control.

Table 5. Effects of increasing amounts of potassium and iron on some element contents of maize leaves

Potassium (K) doses mM	Iron (Fe) doses								
	Fe1, 30 µM		Fe2, 60 µM		Fe3, 90 µM		Fe4, 120 µM		Means
Iron contents mg kg^{-1}									
K1, 1 mM	33.39 a	B	37.73 ab	AB	33.13 b	B	44.95 a	A	37.30 b
K2, 2 mM	27.22 ab	A	27.23 c	A	30.59 b	A	33.41 b	A	29.61 c
K3, 4 mM	24.07 b	B	32.13 bc	A	34.38 b	A	34.68 b	A	31.32 c
K4, 6 mM	21.34 b	C	30.39 bc	B	33.78 b	B	47.31 a	A	33.21 c
K5, 8 mM	32.73 a	B	44.22 a	A	44.26 a	A	44.71 a	A	41.48 a
Means	27.75	C	34.34	B	35.23	B	41.01	A	
$Fe_{LSD<0.01}$: 3.604			$K_{LSD<0.01}$: 4.030				$Fe*K_{LSD<0.01}$: 8.059		
Active iron contents mg kg^{-1}									
K1, 1 mM	13.30 ab	B	22.52 ab	B	24.68 c	B	27.12 b	A	21.91 b
K2, 2 mM	20.06 a	A	24.37 ab	A	26.11 bc	A	24.41 b	A	23.74 b
K3, 4 mM	11.64 b	C	20.29 b	B	34.38 a	A	27.30 b	AB	23.40 b
K4, 6 mM	18.76 a	C	22.47 ab	C	32.97 ab	B	42.01 a	A	29.05 a
K5, 8 mM	18.28 ab	B	28.65 a	AB	22.06 c	B	29.01 b	A	24.50 b
Means	16.41	C	23.66	B	28.04	A	29.97	A	
$Fe_{LSD<0.01}$: 3.180			$K_{LSD<0.01}$: 3.555				$Fe*K_{LSD<0.01}$: 7.110		
Potassium contents %									
K1, 1 mM	5.82 c	A	3.01 d	B	1.78 d	C	1.77 d	C	3.10 e
K2, 2 mM	7.88 b	A	4.16 c	B	3.41 c	B	2.58 c	C	4.51 d
K3, 4 mM	8.90 a	A	5.12 b	B	3.94 c	C	3.92 b	C	5.47 c
K4, 6 mM	8.23 ab	A	6.27 a	B	5.66 b	B	4.51 b	C	6.17 b
K5, 8 mM	7.51 b	A	6.96 a	AB	7.39 a	AB	6.67 a	B	7.13 a
Means	7.67	A	5.11	B	4.44	C	3.89	D	
$Fe_{LSD<0.01}$: 0.336			$K_{LSD<0.01}$: 0.376				$Fe*K_{LSD<0.01}$: 0.752		
Nitrogen contents %									
K1, 1 mM	2.63 b	B	3.22 a	A	2.52 a	B	2.46 a	B	2.71 a
K2, 2 mM	3.28 a	A	3.33 a	A	2.56 a	B	2.06 bc	C	2.81 a
K3, 4 mM	2.85 b	A	2.25 b	B	1.96 b	BC	1.76 c	C	2.21 b
K4, 6 mM	2.97 ab	A	2.39 b	B	1.96 b	C	1.87 bc	C	2.30 b
K5, 8 mM	2.22 c	A	2.07 b	A	2.15 b	A	2.16 ab	A	2.15 b
Means	2.79	A	2.65	A	2.23	B	2.06	C	
$Fe_{LSD<0.01}$: 0.161			$K_{LSD<0.01}$: 0.179				$Fe*K_{LSD<0.01}$: 0.359		
Phosphorus contents %									
K1, 1 mM	1.60 a	A	1.31 a	B	1.03 a	C	1.15 a	BC	1.27 a
K2, 2 mM	1.69 a	A	1.23 a	B	0.95 a	C	0.75 b	C	1.16 b
K3, 4 mM	0.98 b	A	0.62 b	B	0.53 b	B	0.54 bc	B	0.67 c
K4, 6 mM	0.68 c	A	0.47 b	AB	0.45 b	AB	0.41 c	B	0.50 d
K5, 8 mM	0.35 d	A	0.40 b	A	0.43 b	A	0.42 c	A	0.40 d
Means	1.06	A	0.81	B	0.68	C	0.66	C	
$Fe_{LSD<0.01}$: 0.102			$K_{LSD<0.01}$: 0.114				$Fe*K_{LSD<0.01}$: 0.228		
Magnesium content %									
K1, 1 mM	0.49 a	C	0.97 a	A	0.80 a	B	0.94 a	AB	0.80 a
K2, 2 mM	0.48 ab	B	0.60 b	AB	0.67 b	A	0.57 b	AB	0.58 b
K3, 4 mM	0.41 ab	A	0.42 c	A	0.32 b	A	0.37 c	A	0.38 c
K4, 6 mM	0.46 ab	A	0.29 c	B	0.31 b	AB	0.28 c	B	0.34 c
K5, 8 mM	0.33 b	A	0.35 c	A	0.36 b	A	0.34 c	A	0.34 c
Means	0.43	B	0.53	A	0.49	A	0.50	A	
$Fe_{LSD<0.05}$: 0.054			$K_{LSD<0.01}$: 0.081				$Fe*K_{LSD<0.01}$: 0.163		
Calcium contents %									
K1, 1 mM	0.59 ab	AB	0.67 a	A	0.55 a	B	0.65 a	A	0.61 a
K2, 2 mM	0.67 a	A	0.54 b	B	0.55 a	B	0.44 b	C	0.55 b
K3, 4 mM	0.56 b	A	0.42 c	B	0.36 b	B	0.37 bc	B	0.43 c
K4, 6 mM	0.45 c	A	0.36 c	AB	0.36 b	AB	0.33 c	B	0.37 d
K5, 8 mM	0.35 c	A	0.36 c	A	0.38 b	A	0.38 bc	A	0.37 d
Means	0.52	A	0.47	B	0.44	B	0.44	B	
$Fe_{LSD<0.01}$: 0.044			$K_{LSD<0.01}$: 0.049				$Fe*K_{LSD<0.01}$: 0.098		

Note. Explanations under Table 2.

Table 6. Effects of increasing amounts of potassium and iron on some element contents of maize roots

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
			Iron contents mg kg^{-1}		
K1, 1 mM	933.77	1334.33	1831.33	1724.33	1455.94 a
K2, 2 mM	830.07	1086.73	1212.33	1180.03	1077.29 b
K3, 4 mM	593.47	626.10	1086.97	1353.67	915.05 bc
K4, 6 mM	451.03	794.13	1268.13	1180.73	923.51 bc
K5, 8 mM	435.10	888.63	907.03	896.03	781.70 c
Means	648.69 C	945.99 B	1261.16 A	1266.96 A	
$Fe_{LSD<0.01}$: 212.273		$K_{LSD<0.01}$: 237.328		Fe*K: ns	
			Potassium contents %		
K1, 1 mM	2.79 d A	1.46 d B	1.10 e B	1.09 d B	1.61 e
K2, 2 mM	4.41 c A	2.38 c B	1.91 d BC	1.41 d C	2.53 d
K3, 4 mM	5.80 b A	3.58 b B	3.54 c B	2.43 c C	3.84 c
K4, 6 mM	6.82 a A	5.73 a B	4.25 b C	4.08 b C	5.22 b
K5, 8 mM	7.08 a A	5.59 a B	6.99 a A	6.69 a A	6.59 a
Means	5.38 A	3.75 B	3.56 B	3.14 C	
$Fe_{LSD<0.01}$: 0.272		$K_{LSD<0.01}$: 0.304		$Fe*K_{LSD<0.01}$: 0.607	
			Nitrogen contents %		
K1, 1 mM	3.31 a A	3.02 a B	2.07 a C	2.00 a C	2.60 a
K2, 2 mM	3.34 a A	2.96 a B	1.86 ab C	1.63 b C	2.45 b
K3, 4 mM	3.10 a A	1.81 b B	1.73 bc BC	1.53 b C	2.04 c
K4, 6 mM	2.69 b A	1.75 b B	1.54 c B	1.60 b B	1.90 d
K5, 8 mM	1.93 c A	1.84 b A	1.79 b A	1.78 ab A	1.83 d
Means	2.88 A	2.28 B	1.80 C	1.71 C	
$Fe_{LSD<0.01}$: 0.111		$K_{LSD<0.01}$: 0.124		$Fe*K_{LSD<0.01}$: 0.248	
			Phosphorus contents %		
K1, 1 mM	2.07 a A	1.66 a B	1.00 a C	0.97 a C	1.43 a
K2, 2 mM	2.11 a A	1.52 a B	0.94 a C	0.80 ab C	1,34 a
K3, 4 mM	1.19 b A	0.90 b BC	0.92 a B	0.70 bc C	0.93 b
K4, 6 mM	0.80 c A	0.69 c AB	0.71 b AB	0.58 c B	0.69 c
K5, 8 mM	0.49 d A	0.50 c A	0.57 b A	0.56 c A	0.53 d
Means	1.33 A	1.05 B	0.83 C	0.72 D	
$Fe_{LSD<0.01}$: 0.089		$K_{LSD<0.01}$: 0.100		$Fe*K_{LSD<0.01}$: 0.199	
			Magnesium contents %		
K1, 1 mM	1.20 a A	1.27 a A	1.17 a A	1.14 a A	1.19 a
K2, 2 mM	1.31 a A	1.33 a A	1.10 ab B	1.22 a AB	1.24 a
K3, 4 mM	0.89 b B	1.21 a A	0.97 b B	0.97 b B	1.01 b
K4, 6 mM	0.70 c AB	0.68 b AB	0.76 c A	0.60 c B	0.68 c
K5, 8 mM	0.55 c AB	0.64 b A	0.48 d B	0.49 c AB	0.54 d
Means	0.93 B	1.02 A	0.89 B	0.89 B	
$Fe_{LSD<0.01}$: 0.091		$K_{LSD<0.01}$: 0.102		$Fe*K_{LSD<0.05}$:0.153	
			Calcium contents %		
K1, 1 mM	0.83 a B	1.17 ab A	1.13 b A	1.04 b AB	1.04 b
K2, 2 mM	0.94 a B	1.08 ab AB	0.96 b B	1.31 ab A	1.07 b
K3, 4 mM	0.87 a B	1.01 b B	1.45 a A	1.56 a A	1.22 a
K4, 6 mM	0.79 a B	0.96 b B	1.54 a A	1.26 ab A	1.14 ab
K5, 8 mM	1.03 a B	1.34 a A	1.06 b AB	1.02 b B	1.11 ab
Means	0.89 B	1.11 B	1.23 A	1.24 A	
$Fe_{LSD<0.01}$: 0.136		$K_{LSD<0.05}$: 0.113		$Fe*K_{LSD<0.01}$: 0.303	

Notes. The differences between values indicated by different letters are significant. Capital letters indicate rows and small letters indicate columns. ns: not significant.

Table 7. Effects of increasing amounts of potassium and iron on some element uptake of maize leaves (mg tdw^{-1})

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
1	2	3	4	5	6
			Iron uptake mg tdw^{-1}		
K1, 1 mM	0.56 b C	1.91 bc BC	2.70 bc AB	3.89 b A	2.27 b
K2, 2 mM	0.84 b C	1.49 c BC	2.42 c B	4.05 b A	2.20 b
K3, 4 mM	1.13 b C	3.07 ab B	4.00 ab AB	5.05 b A	3.31 a
K4, 6 mM	1.04 b D	2.83 abc C	4.28 a B	6.80 a A	3.74 a
K5, 8 mM	2.73 a B	4.22 a A	3.77 abc AB	4.16 b A	3.72 a
Means	1.26 D	2.70 C	3.43 B	4.79 A	
	$Fe_{LSD<0.01}$: 0.638		$K_{LSD<0.01}$: 0.713	$Fe*K_{LSD<0.01}$: 1.426	
			Active iron uptake mg tdw^{-1}		
K1, 1 mM	0.23 a B	1.14 b AB	2.01 b A	2.35 c A	1.43 d
K2, 2 mM	0.62 a C	1.34 b BC	2.07 b AB	2.96 bc A	1.75 cd
K3, 4 mM	0.55 a C	1.93 ab B	4.11 a A	3.97 b A	2.64 ab
K4, 6 mM	0.91 a C	2.10 ab C	4.20 a B	6.02 a A	3.31 a
K5, 8 mM	1.53 a A	2.73 a A	1.85 b A	2.73 bc A	2.21 bc
Means	0.77 D	1.85 C	2.85 B	3.61 A	
	$Fe_{LSD<0.01}$: 0.602		$K_{LSD<0.01}$: 0.673	$Fe*K_{LSD<0.01}$: 1.346	
			Potassium uptake mg tdw^{-1}		
K1, 1 mM	974.63 d A	1524.66 c A	1476.46 d A	1670.72 c A	1411.62 d
K2, 2 mM	2423.91 c A	2285.73 c A	2669.98 c A	3115.75 b A	2623.84 c
K3, 4 mM	4100.45 b B	4892.27 b AB	4600.06 b AB	5687.70 a A	4820.12 b
K4, 6 mM	3983.82 b C	5837.39 ab B	7123.46 a A	6488.24 a AB	5858.23 a
K5, 8 mM	6252.97 a A	6636.34 a A	6197.07 a A	6119.18 a A	6301.39 a
Means	3547.16 B	4235.28 AB	4413.41 A	4616.32 A	
	$Fe_{LSD<0.01}$: 712.575		$K_{LSD<0.01}$: 796.684	$Fe*K_{LSD<0.05}$: 1190.593	
			Nitrogen uptake mg tdw^{-1}		
K1, 1 mM	0.44	1.62	2.06	2.12	1.56 b
K2, 2 mM	1.01	1.84	2.03	2.50	1.84 ab
K3, 4 mM	1.33	2.15	2.30	2.56	2.08 a
K4, 6 mM	1.43	2.23	2.48	2.68	2.21 a
K5, 8 mM	1.83	1.98	1.80	2.02	1.91 ab
Means	1.21 C	1.97 B	2.13 AB	2.38 A	
	$Fe_{LSD<0.01}$: 0.351		$K_{LSD<0.01}$: 0.393	$Fe*K_{LSD}$: ns	
			Phosphorus uptake mg tdw^{-1}		
K1, 1 mM	267.05 c C	664.17 a B	851.00 a A	982.77 a A	691.25 a
K2, 2 mM	513.60 a C	677.27 a BC	744.78 ab AB	907.93 ab A	710.89 a
K3, 4 mM	456.02 ab B	586.97 ab B	622.52 b AB	781.48 b A	611.75 a
K4, 6 mM	329.54 abc B	433.16 abc AB	571.98 b A	590.69 c A	481.34 b
K5, 8 mM	297.45 bc A	380.10 bc A	361.15 c A	395.19 d A	358.47 b
Means	372.73 C	548.33 B	630.28 AB	731.61 A	
	$Fe_{LSD<0.01}$: 111.545		$K_{LSD<0.01}$: 124.711	$Fe*K_{LSD<0.05}$: 186.373	
			Magnesium uptake mg tdw^{-1}		
K1, 1 mM	81.69 b C	489.71 a B	655.55 a A	795.15 a A	505.53 a
K2, 2 mM	147.51 ab D	330.65 b C	527.29 ab B	686.64 b A	423.03 b
K3, 4 mM	188.84 ab B	395.63 ab AB	368.25 c B	531.20 b A	370.98 bc
K4, 6 mM	211.81 ab B	266.55 b AB	389.80 bc A	406.07 bc A	318.56 c
K5, 8 mM	267.30 a A	327.92 b A	294.89 c A	311.53 c A	300.41 c
Means	179.43 D	362.09 C	447.16 B	546.12 A	
	$Fe_{LSD<0.01}$: 63.850		$K_{LSD<0.01}$: 71.386	$Fe*K_{LSD<0.01}$: 142.773	

Table 7 continued

1	2	3	4	5	6
			Calcium uptake mg tdw^{-1}		
K1, 1 mM	98.41 b C	337.10 a B	448.58 ab AB	551.05 a A	358.79 ab
K2, 2 mM	205.41 ab C	297.58 a BC	427.27 ab AB	540.12 a A	367.59 ab
K3, 4 mM	255.83 a C	403.88 a B	425.35 ab AB	540.41 a A	406.37 a
K4, 6 mM	216.87 ab C	331.15 a BC	462.91 a AB	472.61 ab A	370.88 ab
K5, 8 mM	289.28 a A	343.36 a A	316.37 b A	350.70 b A	324.93 b
Means	213.16 D	342.62 C	416.10 B	490.98 A	
$Fe_{LSD<0.01}$: 59.486		$K_{LSD<0.05}$: 49.696		$Fe*K_{LSD<0.01}$: 133.016	

Notes. The differences between values indicated by different letters are significant. Capital letters indicate rows and small letters indicate columns. tdw: total dry weight; ns: not significant.

Table 8. Effects of increasing amounts of potassium and iron on some element uptake of maize roots (mg tdw^{-1})

Potassium (K) doses mM	Iron (Fe) doses				
	Fe1, 30 µM	Fe2, 60 µM	Fe3, 90 µM	Fe4, 120 µM	Means
1	2	3	4	5	6
			Iron uptake mg tdw^{-1}		
K1, 1 mM	5.22 a B	15.54 ab B	35.98 ab A	33.04 c A	22.45 c
K2, 2 mM	7.93 a B	12.92 b B	29.69 b A	35.71 bc A	21.56 c
K3, 4 mM	9.94 a C	17.31 ab C	35.25 ab B	53.88 a A	29.10 ab
K4, 6 mM	5.75 a C	20.99 ab B	48.33 a A	48.48 ab A	30.89 a
K5, 8 mM	11.23 a B	26.01 a A	26.41 b A	32.35 c A	24.00 bc
Means	8.02 C	18.55 B	35.13 A	40.69 A	
$Fe_{LSD<0.01}$: 7.829		$K_{LSD<0.01}$: 6.541		$Fe*K_{LSD<0.01}$: 13.081	
			Potassium uptake mg tdw^{-1}		
K1, 1 mM	156.61 c A	172.41 c A	220.63 c A	209.30 d A	189.74 d
K2, 2 mM	420.58 c A	286.62 c A	476.38 c A	429.72 d A	403.33 d
K3, 4 mM	919.06 b A	985.15 b A	1140.73 b A	978.78 c A	1005.93 c
K4, 6 mM	860.07 b B	1532.25 a A	1641.08 a A	1659.83 b A	1423.31 b
K5, 8 mM	1771.81 a BC	1619.67 a C	2033.23 a AB	2385.37 a A	1952.52 a
Means	825.63 B	919.22 AB	1102.41 A	1132.60 A	
$Fe_{LSD<0.01}$: 239.922		$K_{LSD<0.01}$: 268.241		$Fe*K_{LSD<0.05}$:400.869	
			Nitrogen uptake mg tdw^{-1}		
K1, 1 mM	0.19	0.35	0.41	0.39	0.33 c
K2, 2 mM	0.32	0.36	0.46	0.49	0.41 bc
K3, 4 mM	0.49	0.50	0.56	0.61	0.54 a
K4, 6 mM	0.34	0.47	0.60	0.65	0.51 ab
K5, 8 mM	0.48	0.53	0.52	0.64	0.54 a
Means	0.36 C	0.44 BC	0.51 AB	0.56 A	
$Fe_{LSD<0.01}$: 0.095		$K_{LSD<0.01}$: 0.106		$Fe*K_{LSD}$: ns	
			Phosphorus uptake mg tdw^{-1}		
K1, 1 mM	116.16	194.48	198.20	186.71	173.89 bc
K2, 2 mM	200.46	180.96	231.98	242.18	213.90 ab
K3, 4 mM	191.03	248.26	296.86	282.07	254.55 a
K4, 6 mM	100.80	184.35	269.32	236.11	197.64 bc
K5, 8 mM	126.82	145.44	168.60	200.05	160.22 c
Means	147.05 B	190.70 A	232.99 A	229.42 A	
$Fe_{LSD<0.01}$: 42.906		$K_{LSD<0.01}$: 47.970		$Fe*K_{LSD}$: ns	

Table 8 continued

1	2	3	4	5	6
Magnesium uptake mg tdw^{-1}					
K1, 1 mM	67.50 a B	148.85 b AB	229.50 a A	219.58 b A	166.36 cd
K2, 2 mM	125.81 a C	158.04 b C	275.59 a B	366.62 a A	231.52 b
K3, 4 mM	141.85 a B	331.89 a A	310.21 a A	380.90 a A	291.21 a
K4, 6 mM	87.62 a C	182.36 b B	294.32 a A	245.90 b AB	202.55 bc
K5, 8 mM	137.46 a A	185.95 b A	136.92 b A	172.85 b A	158.30 d
Means	112.05 C	201.42 B	249.31 A	277.17 A	
$Fe_{LSD <0.01}$: 37.487		$K_{LSD <0.01}$: 41.912		$Fe*K_{LSD <0.01}$: 83.824	
Calcium uptake mg tdw^{-1}					
K1, 1 mM	46.28 b B	136.42 bc AB	221.87 b A	199.74 d A	151.08 b
K2, 2 mM	89.49 b C	129.22 c BC	239.66 b B	392.22 bc A	212.65 b
K3, 4 mM	141.07 ab C	280.68 ab C	464.37 a B	619.80 a A	376.48 a
K4, 6 mM	100.48 b C	255.08 abc B	592.16 a A	518.59 ab A	366.58 a
K5, 8 mM	261.38 a A	389.76 a A	308.96 b A	362.39 c A	330.62 a
Means	127.74 C	238.23 B	365.40 A	418.55 A	
$Fe_{LSD <0.01}$: 66.972		$K_{LSD <0.01}$: 74.88		$Fe*K_{LSD <0.01}$:149.753	

Notes. Explanations under Table 7.

The effects of increasing amounts of K and Fe on some macro element concentrations in both leaves and roots of maize and their uptake are shown in Tables 5–8. The addition of increasing levels of K enhanced the concentrations and the uptake of K into leaves and roots. While the highest concentrations in leaves (8.90%) and in roots (7.08%) were measured at the K3Fe1 and K5Fe1 applications, the highest uptakes (7123.46 mg tdw^{-1} and 2385.37 mg tdw^{-1}) were found at K4Fe3 and K5Fe4, respectively. Although the increasing amounts of Fe lowered the concentrations of K due to the dilution effect, it enhanced their uptake both in leaves and roots.

The addition of increasing levels of K and Fe affected the N, P, Mg and Ca concentrations negatively in both leaves and roots of maize (Tables 5–8). In the leaves, the highest N concentration was measured as 3.33% at K2Fe2 application and the lowest concentration was determined as 1.76% at K3Fe4 (Table 5). In the roots, the lowest concentration was also measured at K3Fe4 as 1.53% and the maximum amount (3.34%) was measured at K2Fe1 application (Table 6). The addition of increasing levels of K and Fe decreased the concentrations of P in both the leaves and roots. While the highest concentrations in leaves (1.69%) and in roots (2.11%) were measured at the K2Fe1 application, the lowest concentrations (0.35% and 0.49%) were found at K5Fe1, respectively. The highest Mg and Ca concentrations in the leaves (0.97% and 0.67%) were measured at K1Fe2 application, the lowest concentrations (0.28% and 0.33%) were determined at K4Fe4 application (Table 5). As shown in the leaves, Mg and Ca concentrations of the roots were also affected negatively with the application of high doses of K and Fe. The highest amounts for Mg and Ca were determined at K2Fe2 and K2Fe4 and the lowest amounts were determined at K5Fe3 and K4Fe1, respectively (Table 6).

The uptake of N, P, Mg and Ca in the leaves increased with increasing amounts of Fe and K but the amounts lowered with high K applications. High amounts of Fe also decreased the P, Mg and Ca uptake in the roots. While the highest uptakes of P, Mg and Ca in the leaves were determined at K1Fe4, the highest Mg and Ca uptake of roots were measured at K3Fe4 (Table 8).

Leigh and Wyn Jones (1984) reported that adequate K is needed to maintain N metabolism. Various researchers (Ruiz, Romero, 2002; Pervez et al., 2006) also stated the need of adequate K for the efficient use of N. In N metabolism N can be absorbed by plants as either a cation or an anion. This presents the unique possibility of both an anion-cation as well as a cation-cation interaction with K. Phosphorus also requires adequate levels of K for maximum crop response and also reported a potential K-P interaction in the uptake. Some of them demonstrated positive interaction and in contrast others reported antagonistic ionic interaction (Pervez et al., 2006).

Increasing doses of K have a fairly consistent effect on lowering the concentrations of Ca and Mg in most plant species. With excess K applications a strong antagonism between K and Ca and also Mg were reported (Marchner, 1995; Garcia et al., 1999). Because of probable competition with other cations, the other nutrient contents of both leaves and roots also tended to decrease with increasing K and Fe applications. Potassium has an impact on the uptake of other cationic species and thus may affect the crop yield and the crop quality (Mengel, 2007). K interacts with almost all of the essential macronutrients, the secondary nutrients and the micronutrients (Pervez et al., 2006). Potassium is absorbed rapidly, and this causes competition for the uptake of other cations (Demiral, Köseoğlu, 2005). K is a very strong competitor in this competition. If K is present in a relatively high concentration, it affects the uptake of other cations such as Na^{+}, Mg^{+2} and Ca^{+2}. If K is not present in the nutrient solution, the other cationic species are taken up at higher rates (Mengel, 2007). The high amounts of Fe also affect the behaviour of K and its interaction between other cations.

Conclusions

1. Both K and Fe deficiencies cause poor development and chlorosis symptoms in the maize plant.

2. Increasing the amounts of the nutrients stimulates the plant growth, the dry matter yield, the concentrations of the nutrients in the plant and their uptake.

3. The highest doses have a negative effect on growth and some macronutrient element contents of the maize plant. The highest dose of iron lowers the K, N and P contents in the leaves and roots of the maize plant. The highest dose of potassium not only lowers the potassium amounts in the plant but also decreases SPAD values, the uptake of Fe, P, Mg, and Ca and their contents in the leaves and roots of the maize plant.

4. Adequate K may be required for the efficient use of both Fe and other macronutrient elements. However, too high a concentration of K will cause competition with iron and other cations.

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Kalio ir geležies įtaka kukurūzų makroelementų įsisavinimui

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Santrauka

Tyrimai atlikti siekiant nustatyti kalio (K) ir geležies (Fe) įvairių normų įtaką kukurūzų augimui ir kai kurių makroelementų įsisavinimui. Šiuo tikslu recirkuliacinėje hidroponinėje sistemoje kukurūzų (*Zea mays* L. veislė BSC 6661) augalams buvo panaudotos penkios K (1, 2, 4, 6 ir 8 mM) ir keturios Fe (30, 60, 90 ir 120 µM) normos. K ir Fe kiekio didėjimas turėjo teigiamą įtaką kukurūzų lapų ir šaknų sausai masei. Bendroji Fe bei aktyvioji Fe koncentracijos ir jų įsisavinimas padidėjo tirpale didėjant Fe bei K kiekiui, bet šis kiekis sumažėjo, esant didžiausiai K normai. Didesnis K kiekis sumažino P, Mg ir Ca koncentraciją kukurūzų šaknyse bei lapuose. Nors mažiausios K ir Fe normos turėjo teigiamą įtaką, didesnis K ir Fe kiekis sumažino jų įsisavinimą šaknyse ir lapuose.

Reikšminiai žodžiai: aktyvi geležis, antagonizmas, hidroponinė sistema, sąveika.