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Reducing Iron Toxicity in Lowland Rice with Tolerant Genotypes and Plant Nutrition

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ABSTRACT

Iron toxicity is a widespread nutrient disorder of lowland rice grown in tropical and sub-tropical regions of the world on acid sulfate soils, Ultisols and sandy soils with a low cation exchange capacity, moderate to high in acidity, high in easily reducible or active iron and low to moderately high in organic matter. The stress is caused by a high concentration of ferrous iron in soil solution. It is estimated that iron toxicity reduces lowland rice yields by 12-100%, depending on the iron tolerance of the genotype, intensity of the iron toxicity stress and soil fertility status. Iron toxicity can be reduced by using iron-tolerant rice genotypes and through soil, water and nutrient management practices. The objective of this paper is to critically assess the pertinent literature on the role of iron-tolerant rice genotypes and other plant nutrients in reducing iron toxicity in lowland rice. It is emphasized that research should provide knowledge that would be used for increasing lowland rice production and productivity on iron-toxic wetlands on a sustainable basis by integration of genetic tolerance to iron toxicity with soil, water and nutrient management.

Keywords: ferrous iron in soil solution, integrated approach to manage iron toxicity, iron toxicity stress, rice tolerance to iron, rice yield loss, role of other plant nutrients

CONTENTS

INTRODUCTION

Since the first report of its occurrence (Ponnamperuma *et al.* 1955), iron toxicity in lowland rice has been reported to be widespread in several countries, especially in the humid tropical regions in Asia, South America and West and Central Africa (Howeler 1973; van Breemen and Moormann 1978, Yoshida 1981; De Datta *et al.* 1994; Sahrawat *et al.* 1996; Kyuma 2004; Sahrawat 2004; Balasubramanian *et al.* 2007; Fageria *et al.* 2008).

Large areas of wetlands ideally suited for rice production remain underused, especially in Asia, South America and West and Central Africa, because of iron toxicity stress as a constraint (Ponnamperuma 1972; Kyuma 2004; Sahrawat 2004; Balasubramanian *et al.* 2007; Fageria *et al.* 2008). In West Africa, iron toxicity has been reported to reduce rice yields by 12–100% depending on the intensity of the stress and tolerance of the rice cultivars (Abifarin 1988; Sahrawat *et al.* 1996, Sahrawat 2004); and iron toxicity affects rice growth and yield on approximately 30% of the lowland swamp soils in rainfed and irrigated lowland areas in West and Central Africa (Sahrawat 2004).

Ponnamperuma *et al.* (1955) for the first time reported that the bronzing disease of lowland rice grown on soils high in reducible iron under flooded or submerged water condition was associated with a high concentration of ferrous iron in soil solution; and the disorder was caused by iron toxicity (Ponnamperuma *et al.* 1955). The iron toxicity stress in the field occurs in reduced soils when a toxic amount of ferrous iron is mobilized in soil solution *in situ* or when inflow brings in soluble iron from upper slopes (van Breemen and Moormann 1978). A large body of literature on iron toxicity in lowland rice since the first report of its occurrence (Ponnamperuma *et al.* 1955) has confirmed the association of iron toxicity in the rice plant with high but varying amounts of soluble iron in the soil solution or growing media (Sahu 1968; Ponnamperuma 1972, van Breemen and Moormann 1978; Bode *et al.* 1995; Sahrawat 1998; Narteh and Sahrawat 1999; Olaleye *et al.* 2001; Sahrawat 2004, 2005).

Iron toxicity occurs mostly in Ultisols, Oxisols and acid sulfate soils, high in active iron and potential acidity, irrespective of organic matter and texture. But texture, cation exchange capacity and organic matter content influence the concentration of ferrous iron in soil solution, in which iron toxicity occurs (Ponnamperuma 1972; van Breemen and Moormann 1978; Sahrawat 1979; Sahrawat *et al.* 1996; Sahrawat 2004; Fageria *et al.* 2008). Plant and growing medium-related factors such as plant age, acidity reserve and accumulation of hydrogen sulfide, organic acids and other reduction products under reduced soil conditions also are implicated in the occurrence of iron toxicity in the rice plant (Tanaka *et al.* 1968; Yoshida 1981; Genon *et al.* 1994; Sahrawat 2004; Fageria *et al.* 2008).

Iron toxicity symptoms vary with rice cultivars. They are characterized by a reddish brown, yellow, or purple-bronzing or orange discoloration of the lower leaves of the rice plants. Typically, iron toxicity symptoms are manifested as tiny brown spots starting from the upper tips and spreading toward the bases of the lower leaves. With

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progress in iron toxicity, the brown spots coalesce on the interveins of the leaves. With increased iron toxicity stress, the entire affected leaves look purplish brown, followed by drying of the leaves, which gives the rice plant a scorched appearance (Sahrawat *et al.* 1996; Sahrawat 2004). The disorder may be expressed as reduced plant height, reduced tillering, leaf discoloration and loss of chlorophyll, and reduced root growth (Fageria *et al.* 2008). Equally importantly, the roots of rice plants affected by iron toxicity become scanty, coarse, short and blunted and dark brown in color; with the alleviation of the stress, the roots may slowly recover to the usual white color (Sahrawat 2004; Fageria *et al.* 2008). Iron toxicity symptoms on rice leaves and changes in root color and morphology are useful for diagnosis of the stress. The iron toxicity symptoms commonly develop at the maximum tillering and heading growth stage, but may be observed at any growth stage of the rice crop (van Breemen and Moormann 1978).

Iron toxicity is a complex nutrient disorder and the deficiencies of other nutrients, especially phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and zinc (Zn), are considered in the occurrence of (Ottow *et al.* 1983) and tolerance to iron toxicity (for review of literature see Sahrawat 2004). Other nutrients may play an important role not only in reducing the effect of iron toxicity but also in the expression of iron tolerance by various rice cultivars (Sahrawat *et al.* 1996; Sahrawat 2004). Deficiencies of P, K, Ca, Mg and manganese (Mn) decrease the iron-excluding power of rice roots and can thus affect the rice plant's tolerance of iron toxicity (e.g., see Yoshida 1981; Sahrawat 2004). Deficiencies of Ca, Mg and Mn are not commonly observed in lowland rice, except probably on acid sulfate soils; deficiencies of P, K and Zn therefore deserve special attention (Yoshida 1981; Sahrawat *et al.* 1996; Sahrawat 2004).

The objective of this paper is to critically review salient research on the role of tolerant genotypes and plant nutrients in reducing iron toxicity and enhance rice productivity on iron-toxic soils. The ultimate goal is to provide information that can be used for increasing rice production and productivity on iron-toxic wetlands on a sustainable basis.

TOLERANT GENOTYPES FOR REDUCING IRON TOXICITY

Rice cultivars differ in their tolerance for iron toxicity and the selection of rice cultivars with superior iron tolerance is an important component of research for reducing iron toxicity. Genetic differences in adaptation to and tolerance for iron-toxic soil conditions have indeed been exploited for developing rice cultivars with tolerance for iron toxicity (Virmani 1977; Yoshida 1981; Gunawardena *et al.* 1982, Abifarin 1988; Winslow *et al.* 1989; DeDatta *et al.* 1994; Sahrawat and Sika 2002; Sahrawat 2004; Balasubramanian *et al.* 2007; Nozoe *et al.* 2008).

Research on the screening of rice cultivars for iron tolerance has also been conducted under controlled conditions in nutrient solution experiments to identify cultivars that are tolerant to high iron as well as to establish the role of various factors in the mechanisms involved in the occurrence of and tolerance to iron toxicity (Patrick 1966; Tanaka *et al.* 1966; Fageria and Rabelo 1987; Bode *et al.* 1995; Asch *et al.* 2005). The reported levels of iron in culture solution that cause iron toxicity have a wide range and vary from as low as10 to >500 mg Fe L^{-1} (Tanaka *et al.* 1966; Patrick 1966; Fageria and Rabelo 1987; Bode *et al.* 1995; Asch *et al.* 2005). It has been observed that during most solution culture experiments no precautions were taken to prevent the oxidation of soluble ferrous iron to insoluble ferric hydroxides and hence the real concentrations of ferrous iron might have been lower than those reported in such studies (van Breemen and Moormann 1978; Sahrawat 2004). For example, Bode *et al.* (1995) in study of iron toxicity in a hydroponic system reported that 5-10% of the ferrous iron was indeed oxidized to ferric iron in experiments lasting 3-4 weeks. On the other hand, Narteh and Sahrawat (1999) observed that an iron-toxic Ultisol released 50 to 150 mg ferrous iron L^{-1} in soil solution during 3-10 weeks after flooding in greenhouse pots; and in the field experiment, rice plants growing on the soil showed severe iron toxicity symptoms (Sahrawat *et al.* 2001). Thus, under field conditions, depending on the land hydrology, both ferrous iron inflow from upper slopes and the in situ release of ferrous iron contribute to the occurrence of iron toxicity to rice (Sahrawat 2004). Such factors relating to the inflow of iron from upper slopes and the in situ generation of ferrous iron in the entire soil profile are not considered in solution culture experiments (Sahrawat *et al.* 1996, 2001).

Thus it is not entirely surprising that contradictory results on the iron-toxicity tolerance of rice cultivars have been reported by employing solution culture and field studies (van Breemen and Moormann 1978; Sahrawat 2004). The use of standard iron-toxicity tolerant and iron-toxicity susceptible rice cultivars in experiments used for screening cultivars for iron-toxicity tolerance can be very valuable (Sahrawat *et al.* 1996, 2001). With lessons learnt from the past research in this area, it is suggested that the selection of rice cultivars for iron toxicity tolerance is better expressed in the field and is greatly influenced by the length of the growing season, which especially facilitates the maintenance of root growth until the late stage of the rice crop growth (Sahrawat 2000; Sahrawat 2004; Nozoe *et al.* 2008).

With emphasis on the application of results on the management of iron toxicity in practical agriculture, this paper mainly focuses on the results obtained in the studies made under field conditions.

Breeding and screening efforts at the International Rice Research Institute in the Philippines and at WARDA (West Africa Rice Development Association, now Africa Rice Center) have identified a number of rice cultivars with improved tolerance to iron for growing in iron-toxic soils (De Datta *et al.* 1994, Sahrawat 2004; Balasubramanian *et al.* 2007; Nozoe *et al.* 2008).

Sahrawat *et al.* (1996) evaluated 20 lowland rice cultivars for tolerance of iron toxicity at an iron-toxic site in Korhogo, Côte d'Ivoire, under irrigated conditions. The cultivars differed in iron-toxicity tolerance. Grain yields varied from 0.10 to 5.04 t ha^{-1} and iron toxicity scores, based on the extent of bronzing symptoms on foliage, ranged from 2 to 9 (1 indicates normal growth and nine indicates that most plants are dead or dying). Further evaluation of rice cultivars during 1992-97 showed that among three promising iron-tolerant cultivars, CK 4 was the top yielder (mean grain yield 5.33 t ha^{-1}), followed by WITA 1 (4.96 t ha^{-1}) and WITA 3 (4.46 t ha^{-1}) and tolerant check Suakoko 8 (3.80 t ha^{-1}) (**Table 1**). These and other results suggest that high rice yields and iron toxicity tolerance are physiologically compatible (Sahrawat *et al.* 2000; Audebert and Sahrawat 2000; da Silveira *et al.* 2007).

Work done by WARDA in West Africa showed that some *Oryza glaberrima* cultivars, adapted to lowland rice-growing conditions, possess a higher tolerance for iron toxicity than their *O. sativa* counterparts. Sahrawat and Sika (2002) conducted experiments at an iron-toxic site (Korhogo, Côte d'Ivoire) during the 2000 wet and dry seasons to evaluate the performance of promising *O. sativa* (CK 4, tolerant check; Bouake 189, susceptible check) and *O. glaberrima* (CG 14) cultivars. While CK 4 and Bouake 189 showed typical iron toxicity symptoms in varying degrees, CG 14 plants did not show any iron toxicity symptoms at all as measured by iron toxicity scores. Although CG 14 did not give high grain yields because of its lower harvest index, lodging of the crop, especially under the application of nutrients and shattering of seeds at maturity, the cultivar showed remarkable tolerance for iron toxicity. Research showed that CG 14 has a high tolerance for iron toxicity and remains an obvious choice as a donor for iron tolerance in breeding programs (Sahrawat and Sika 2002; Sahrawat 2004).

With the objective to select suitable lowland rice vari-

Table 1 Grain yields (t ha^{-1}) of WITA 1 and WITA 3 rice cultivars during 1992-97 relative to the performance of iron-tolerant (Suakoko 8 and CK 4) and iron-susceptible (Bouake 189) check cultivars under irrigated conditions in the wet season at an iron-toxic site in Korhogo, Côte d'Ivoire.[a]

Year	CK4	WITA1	WITA 3	Bouake 189	Suakoko 8	LSD (0.05)
1992	–	4.33	5.04	2.87	4.85	1.080
1993	5.87	5.53	5.17	4.08	5.07	0.630
1994	6.05	6.66	4.30	4.69	3.73	1.100
1996	3.76	3.24	3.21	2.81	2.57	0.760
1997	5.63	5.02	4.59	4.99	2.79	1.345
Mean	5.33	4.96	4.46	3.88	3.80	

[a]Each season, all cultivars received a uniform application of 100 kg N ha^{-1}, 50 kg P ha^{-1} and 10 kg Zn ha^{-1}.

Source: **Sahrawat KL, Diatta S, Singh BN** (2000) Reducing iron toxicity in lowland rice through an integrated use of tolerant genotypes and plant nutrient management. *Oryza* **37**, 44-47, ©2000, Association of Rice Research Workers, Central Rice Research Institute, Cuttack, Orissa, India.

eties for growing in the iron-toxic soils of Orissa, India, Nayak *et al*. (2008) evaluated 65 genotypes for their tolerance to iron in the field by growing them on a typical iron-toxic Haplaquept (pH 5.1; DTPA extractable iron 368 mg kg^{-1}) low in organic matter and cation exchange capacity. The results showed that there was a wide range in tolerance to iron toxicity and iron- tolerant rice genotypes irrespective of their growth duration produced higher grain yields than the iron-susceptible cultivars in the respective duration groups. The grain yield of the rice cultivars evaluated ranged from 0.77 to 3.6 t ha^{-1} and was influenced by tolerance to iron toxicity and growth duration (Nayak *et al*. 2008).

Several physiological mechanisms have been proposed for the tolerance for iron in rice and detailed discussion on the topic has been provided in a review by Sahrawat (2004). Briefly, the physiological status of a rice plant under submerged soil condition greatly modifies its ability to tolerate high iron in soil solution. Rice roots play three important functions to counter iron toxicity and these include (i) oxidation of iron in the rhizosphere to keep iron concentration low in the growth media, (ii) rice roots exclude iron at the root surface and thus prevent iron entering the root and (iii) rice roots are able to retain iron in the root tissue and thus decreases the translocation of iron from the root to the shoot (Tadano 1975). There is another mechanism involved in which the rice plant is able to tolerate a high concentration of iron in the tissue (Sahrawat 2004).

Rice roots diffuse molecular oxygen into the root medium through air chambers and aerenchyma in the rice plant leaves, stems nodes and roots, which makes the rhizosphere more oxidative than the bulk growing soil. This leads to the oxidation of ferrous iron in soil solution to ferric iron, which can be seen as deposits on the surface of the rice roots. The oxidizing power of the rice roots is greater at the growing points and at the elongating parts of the roots than at the basal parts of the roots (Yoshida 1981).

Audebert and Sahrawat (2000) conducted field experiments on iron-toxic soils in an attempt to determine the mechanisms involved in cultivar differences in iron-toxicity tolerance. They found that iron-tolerant rice cultivar absorbed less iron or translocated less iron from the roots to leaves. Also, at any given concentration of iron in the leaves, net photosynthetic rates were lower in the iron-toxicity susceptible than in the iron-toxicity tolerant rice cultivar. The iron-tolerant rice cultivar owed its superior performance under iron-toxic conditions partly to avoidance (less iron accumulation in the photo- synthesizing leaves) and iron tolerance, by maintaining superior photosynthetic potential in the presence of absorbed iron in the leaves (Audebert and Sahrawat 2000). Interestingly, these mechanisms of iron-toxicity tolerance were further enhanced by the applications of other nutrients such as N, P, K and Zn (Audebert and Sahrawat 2000; Sahrawat 2004).

The results discussed in this section clearly bring out that the lowland rice cultivars possess a wide range in genetic tolerance to iron toxicity and this trait could be utilized to select genotypes with superior tolerance to iron. The next step is to build appropriate soil, water and nutrient management practices to go with iron-tolerant genotypes for achieving their potential in the longer-term.

Role of other nutrients in reducing iron toxicity

A high concentration of iron in soil solution can cause nutrient imbalance through antagonistic effects on the uptake of nutrients, including K, P, Mn and Zn (Tanaka and Navasero 1966; Yamauchi 1989; Verma 1991; Sahrawat *et al*. 1996; Sahrawat 1998; Sahu *et al*. 2001; Ramirez *et al*. 2002; Kyuma 2004; Sahrawat 2004, 2007; Fageria *et al*. 2008).

To study the involvement of other plant nutrients in the occurrence of and tolerance to iron toxicity, Sahrawat (2000) determined the elemental composition of iron tolerant (CK 4) and iron susceptible (Bouake 189) lowland rice cultivars grown on an iron-toxic Ultisol (pH 5.4; DTPA extractable iron 490 mg kg^{-1} soil) under irrigated conditions in the field without and with the application of N, P, K and Zn. For both iron-tolerant and iron-susceptible rice varieties, there were no differences in elemental composition of the whole plant tops, sampled at 30 and 60 days after transplanting, except for iron. All the other nutrient element concentrations were in the adequate range (Sahrawat 2000). Both iron-tolerant and iron-susceptible rice varieties had a high concentration, well above the critical limit of 300 mg iron kg^{-1} plant dry wt (**Table 2**). These results showed that iron toxicity is single nutrient (iron) toxicity and not a multiple nutrient deficiency stress.

The results reported by Sahrawat (2000) are in accord with those reported by Sahrawat *et al*. (1996) and da Silveira *et al*. (2007). da Silveira *et al*. (2007) found that except for Mn, the uptake of other nutrients was not impaired by iron toxicity and the effects of iron toxicity were directly due to excess iron rather than the secondary effects of high iron on mineral nutrition of the rice plant.

The deficiency or lack of availability of other nutrients can also affect the rice plant's ability to decrease uptake of iron in the tops through physiological functions carried out by roots such as iron oxidation, iron exclusion and iron retention (Yoshida 1981; Audebet and Sahrawat 2000; Sahrawat 2004). Thus, it is not entirely surprising that the application of other nutrients reduces iron toxicity and improves yield of rice on iron-toxic soils.

Several reports show that the applications of nutrients such as P, K and Zn reduce iron toxicity, improve growth and increase rice yield; and the role, especially of K in reducing iron toxicity in the rice plant has been a subject of several studies (Tanaka and Tadano 1972; Trolldenier 1977; Yamauchi 1989; Ismunadji and Ardjasa 1989; Genon *et al*. 1994; Sahu *et al*. 2001). The effects of other nutrients is not merely as plant nutrient, but their role could be physiological in nature. For example, plant nutrients such as K reduce iron toxicity through enhanced root activity to exclude or retain iron or by influencing the redox-based reactions that influence the amount of iron in soil solution in the rice plant rhizosphere (Tadano and Tanaka 1970; Tadano 1975; Trolldenier 1977; Chen *et al*. 1997; Sahrawat *et al*. 2001; Nayak *et al*. 2004; Sahrawat 2004).

Also, it has been reported that K content of rice plants exhibiting physiological diseases such as Akagare Type 1, bronzing and Akiochi (Park and Tanaka 1968), all linked or attributed to iron toxicity, is often low than in the rice plants free of these physiological disorders (for review see Yoshida

Table 2 Nutrient content (mg kg^{-1}) in plant tops of iron-tolerant (CK 4) and iron-susceptible (Bouake 189) rice varieties grown on an iron-toxic Ultisol without (0) and with (+ NPKZn) treatments at 30 and 60 days after transplanting (DAT) in Korhogo, Côte d'Ivoire.[a]

Nutrient element	At 30 DAT				AT 60 DAT			
	CK 4		Bouake 189		CK 4		Bouake 189	
	0	+NPKZn	0	+NPKZn	0	+NPKZn	0	+NPKZn
N	31,300	31,800	21,900	23,500	15,500	16,600	13,600	14,800
P	3,800	4,100	3,200	3,400	2,800	3,200	3,000	3,300
K	27,500	28,500	34,400	36,500	18,600	22,500	24,600	23,400
Ca	5,100	6,500	1,900	2,100	2,000	2,300	2,000	2,000
Mg	3,600	4,600	1,000	1,100	1,100	1,200	1,200	1,200
Fe	2,897	4,520	3,786	5,730	2,060	1,459	1,607	1,622
Mn	170	155	146	147	224	226	164	201
Zn	60	77	28	25	34	37	37	38

[a] The two rice cultivars received a uniform application of 100 kg N ha^{-1}, 50 kg P ha^{-1} and 10 kg Zn ha^{-1}.
Source: **Sahrawat KL** (2000) Elemental composition of the rice plant as affected by iron toxicity under field conditions. *Communications in Soil Science and Plant Analysis* **31**, 2819-2827, ©2000, Marcel Dekker, NY.

Table 3 Effects of field applications of nutrients on grain yield of iron-tolerant (CK 4) and susceptible (Bouake 189 and TOX 3069-66-2-1-6) rice cultivars on an iron-toxic soil at Korhogo, Côte d'Ivoire (1995-98).[a]

Treatment	Grain yield (t ha^{-1})		
	CK 4	Bouake 189	TOX 3069-66-2-1-6
No fertilizer	4.3 (3)[b]	3.4 (5)	2.9 (7)
N	4.4 (3)	4.1 (5)	3.3 (7)
N + P	5.3 (2)	4.3 (4)	4.2 (5)
N + K	4.8 (2)	4.4 (4)	3.8 (5)
N + Zn	4.8 (2)	4.6 (4)	4.6 (5)
N + P + Zn	5.0 (2)	4.4 (4)	4.2 (4)
N + K + Zn	5.2 (2)	4.6 (3)	4.6 (4)
N + P + K	5.4 (2)	4.5 (3)	4.5 (3)
N + P + K + Zn	5.7 (2)	4.7 (3)	4.7 (3)
LSD (0.05)	1.01	1.02	1.15

[a]The data are an average of four years (1995-98). All cultivars received a uniform application of N (100 kg ha^{-1}), P (50 kg ha^{-1}), K (80 kg ha^{-1}) and Zn (10 kg ha^{-1}).
[b]Iron toxicity scores are given in parentheses on a scale of 1 to 9, where 1 = normal growth and 9 = most plants are dead or drying.
Source: **Sahrawat KL, Diatta S, Singh BN** (2001) Nutrient application reduces iron toxicity in lowland rice in West Africa. *International Rice Research Notes* **26**, 51-52, ©2001, International Rice Research Institute, Los Baños, Philippines.

1981). Deficiencies of K, Ca, Mg, Mn or Si (silicon) decrease the rice roots' ability to retain iron. The rice roots' ability to exclude or retain iron in the rice plant deficient in nutrients such as K, P, Mg, Mn or Si makes such a plant more susceptible to iron toxicity than a healthy plant well supplied with these nutrients (Yoshida 1981; Sahrawat 2004).

Sahrawat *et al.* (2001) conducted field experiments during 1995-1998 to study the effects of applications of N, P, K and Zn in various combinations on the iron toxicity tolerance, indicated by iron toxicity score and grain yield of iron-tolerant and iron-susceptible lowland rice cultivars in iron-toxic Ultisols under irrigated conditions. The results showed that applications of N, P, K and Zn in various combinations reduced iron toxicity and increased yields of iron-tolerant and -susceptible rice cultivars. The increase in grain yields of iron-susceptible cultivars was more than that of iron-tolerant cultivars (**Table 3**). These results clearly demonstrate that a combination of iron-tolerant rice cultivar along with balanced nutrient application provides the best results in terms of reducing iron toxicity and increasing rice yields.

Sahrawat and Sika (2002) conducted experiments under irrigated conditions in the 2000 dry (January-May) and wet season (July-November) on an iron toxic site in West Africa to evaluate the effects of application of other nutrients on the expression of iron toxicity symptoms and grain and biomass production. The lowland rice varieties tested were CK4, an iron-tolerant variety; Bouake 189, an iron-susceptible variety (both belong to *Oryza sativa*); and *Oryza glaberrima* variety CG14, a tolerant variety that does not show iron toxicity symptoms. The results showed that the yields were higher in the wet than in the dry season and the application of P, K or Zn with N increased grain yield and total biomass production over the control (no nutrients applied). The combined applications of N, P, K and Zn significantly increased rice grain and total biomass yields in the three varieties (**Table 4**). However, the response of the *Oryza glaberrima* rice cultivar CG14 to nutrient application was greatly influenced by its lower harvest index, lodging

Table 4 Iron toxicity scores (ITS) of rice plants at 60 d after transplanting and grain and grain plus straw yields of iron-tolerant (CK4 and CG14) and susceptible (Bouake 189) lowland rice cultivars grown on an iron-toxic soil.

Treatment	CK4			Bouake 189			CG14		
	Grain (t ha^{-1})	Biomass (t ha^{-1})	ITS[a]	Grain (t ha^{-1})	Biomass (t ha^{-1})	ITS	Grain (t ha^{-1})	Biomass (t ha^{-1})	ITS
2000 dry season									
No nutrients	2.0	5.4	5	1.6	3.9	6	1.8	3.7	1
N + P + K + Zn	3.2	8.5	2	2.6	5.9	3	2.0	6.0	1
Mean	2.6	6.9		2.1	4.9		1.9	4.8	
LSD (0.05)	0.42	1.60		0.41	1.65		0.31	1.15	
2000 wet season									
No nutrients	2.9	5.6	5	2.4	5.0	5	2.8	5.6	1
N + P + K + Zn	5.9	11.0	2	5.9	12.2	3	3.7	7.8	1
Mean	4.4	8.3		4.2	8.6		3.3	6.7	
LSD (0.05)	1.11	2.01		0.75	1.95		0.67	2.11	
Av of dry and wet seasons									
No nutrients	2.5	5.5	5	2.0	4.4	6	2.3	4.7	1
N + P + K + Zn	4.5	9.8	2	4.2	9.1	3	2.9	6.9	1
LSD (0.05)	0.77	1.91		0.58	1.80		0.50	1.63	

[a] The iron toxicity scoring system is based on the extent of bronzing symptoms on rice plant leaves and uses a scale from 1 to 9. A score of I indicates normal growth and 9 indicates that most plants are dead or dying.
Source: **Sahrawat KL, Sika M** (2002) Comparative tolerance of *Oryza sativa* and *O. glaberrima* rice cultivars for iron toxicity in West Africa. *International Rice Research Notes* **27**, 30-31, ©2002, International Rice Research Institute, Los Baños, Philippines.

of the crop, especially under the application of nutrients and shattering of seeds at maturity, the variety showed remarkable tolerance for iron toxicity stress. The results show that CG14 has a high tolerance for iron toxicity and remains an obvious choice as a donor for iron tolerance in a breeding program (Sahrawat and Sika 2002).

Ramirez *et al*. (2002) conducted a field experiment in La Mata, Dominican Republic to study the role of other nutrients [P, K, sulfur (S) and Zn in combination with N] on the occurrence of and tolerance to iron toxicity in iron-tolerant and susceptible lowland rice cultivars. The results showed that the application of N, P, K, S and Zn reduced the effect of iron toxicity, but did not overcome the stress completely. Iron toxicity symptoms were observed on the rice plants when the DTPA-extractable iron concentration in the flooded soil was higher than 200 mg kg^{-1} soil. The application of nitrogen, phosphorus, potassium, sulfur and zinc nutrients significantly increased the grain yield of all three varieties (both iron-tolerant and sensitive cultivars), but the role of individual nutrients could not be ascertained from the study. The iron-tolerant rice varieties (ISA-40 and PSQ-4) produced high grain yields (mean grain yield of 7.74 t ha^{-1} by PSQ-4 and 8.84 t ha^{-1} by ISA-40) and their yields were significantly higher than those produced by the iron-susceptible rice variety (JUMA-57, mean grain 5.54 t ha^{-1}).

The results reported by Ramirez *et al*. (2002) on the role of other plant nutrients in reducing iron toxicity stress and increasing yields of lowland rice cultivars in the field are in accord with those reported by Sahrawat *et al*. (1996, 2000), Sahrawat and Sika (2002), and Olaleye and Ogunkunle (2008) in field studies.

More importantly, the research reviewed clearly demonstrates that for the best results in terms of rice yield and its sustainability, the use of iron-tolerant rice cultivars should be integrated with balanced nutrient management strategy. Clearly, the role of other plant nutrients (K, Ca, Mg, Mn, S or Si) manifest in a combination of influences relating to the function of roots in reducing iron toxicity in lowland rice (Tadano and Yoshida 1978; Yoshida 1981; Sahrawat 2004).

CONCLUSIONS

The intensified use of iron-toxic wetlands in the future is inevitable for meeting the food needs of the ever-growing population in tropical regions, where iron-toxic soils are an important natural resource for food production. The results discussed in this paper demonstrate that iron toxicity can be reduced by using iron-tolerant cultivars and by applying other nutrients whose availability is negatively affected by a high concentration of iron in soil solution. An integrated use of tolerant genotypes and improved soil and nutrient management is more practical for sustainable increases in rice productivity especially under high and sustained iron toxicity stress.

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