Managing iron toxicity in lowland rice: the role of tolerant genotypes and plant nutrients

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Iron toxicity is a widespread nutrient disorder affecting the growing of wetland rice in the humid tropical regions of Asia, Africa, and South America. Large areas of wetlands ideally suited for rice production remain underused, especially in West and Central Africa, because of iron toxicity as a constraint. 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 (Sahrawat et al 1996, Sahrawat 2004). Iron toxicity of wetland rice is associated with a high concentration of ferrous iron in soil solution (Ponnamperuma et al 1955). The stress 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).

Iron toxicity occurs in soils (mostly 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 (van Breemen and Moormann 1978). Plant- and growing-medium-related factors such as plant age, accumulation of hydrogen sulfide, organic acids, and other reduction products also influence iron toxicity occurrence in rice (Sahrawat 2004).

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 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. Equally important, 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. Iron toxicity symptoms on rice leaves and changes in root color and morphology are useful for diagnosis of the stress. Toxicity symptoms commonly develop at the maximum tillering and heading growth stage, but may be observed at any growth stage of the rice crop.

Since the first report of its occurrence (Ponnamperuma et al 1955), iron toxicity in rice has been reported in several countries in Asia, South America, and West and Central Africa (van Breemen and Moormann 1978, Yoshida 1981, De Datta et al 1994, Sahrawat 2004).

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 iron toxicity in rice (Ottow et al 1983). 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).

This paper critically reviews recent research on the role of tolerant genotypes and plant nutrients in reducing iron toxicity. 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 (Gunawardena et al 1982, DeDatta et al 1994). Breeding and screening efforts at the International Rice Research Institute in the Philippines and at WARDA (West Africa Rice Development Association) in Côte d'Ivoire have identified a number of rice cultivars for growing in iron-toxic soils (De Datta et al 1994, Sahrawat 2004).

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 tolerance of iron toxicity. 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 9 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 tol-

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 et al (2000).

erance are physiologically compatible (Sahrawat et al 2000, Audebert and Sahrawat 2000).

Work done at 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, it showed remarkable tolerance for iron toxicity. Research shows 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).

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 and Zn. 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 applications of nutrients such as P, K, and Zn reduce iron toxicity, improve growth, and increase rice yield (Sahrawat et al 2001, Nayak et al 2004, Sahrawat 2004). Sahrawat et al (2001) 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 2).

Table 2. 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 et al (2001).

Conclusions

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. 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. An integrated use of tolerant genotypes and improved soil and nutrient management is more practical for sustainable increases in rice productivity.

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Notes

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Soil acidity and related problems in upland rice in the tropics

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Upland rice is grown on a total of 19.1 million ha in Asia (60%), Latin America (30%), and Africa (10%). The humid to subhumid climatic conditions prevailing in upland rice areas have typically led to various degrees of soil acidity because of deep weathering and leaching of cations. In fact, the major soils for upland rice are Ultisols and Alfisols in Asia and West Africa, and Oxisols and Ultisols in Latin America. Oxisols and Ultisols are especially typical acid soils.

Soil constraints are less critical for irrigated rice because flooded conditions increase the availability of nutrients and stabilize soil pH closer to neutral, even in acid soils. On upland soils, however, soil acidity can cause yield losses of up to 50% (Sarkarung 1986). It is therefore necessary to manage soil acidity and related soil constraints to increase the productivity of upland rice.

Growth-limiting factors for upland rice in acid soils

The problems of acid soils are complex and are often regarded as an "acid-soil syndrome." The major growth-limiting factor for upland rice differs depending on the degree of soil acidity.

Roughly speaking, where soil pH (in water) is lower than 4.3, the Al concentration in the soil solution can be higher than 100 µM. This is potentially toxic, with negative effects on the elongation of rice roots under solution culture conditions. In upland rice fields, such soil conditions are not the norm but can be induced by inappropriate management practices. For example, in Oxisols in the subhumid savannas of Colombia, this degree of acidity occurred only in the surface soil layer in the middle stage of rice development. This enhanced acidity was created by the sequential split application of urea, which reduced soil pH because of nitrification and by potassium fertilizers that exchange Al at the exchange site of clay minerals and increase Al concentration in soil solution in the moderately intensive upland rice cultivation system (Okada and Fischer 2001).

Rice plants are moderately tolerant of acid soils in general, but showed wide genotypic variation in tolerance of this severe soil acidity. Semidwarf indicas were susceptible but tropical/temperate japonicas were usually tolerant. The causal factor inducing genotypic differences was investigated under these conditions and it was found to be low Ca availability rather than high Al (Okada and Fischer 2001). The relative growth of susceptible varieties was more correlated to exchangeable Ca than to exchangeable Al and Al saturation (Fig. 1). The tolerant genotype had a higher Ca absorbing capacity of the roots, probably owing to higher preferential adsorption of Ca over Al at the surface of the root cell wall (Okada et al 2003).

When soil pH is higher than 4.3, the concentration of Al in soil solution is not toxic to the elongation of rice roots. This is the case for the commonly found acidic soils in West Africa (Ultisols and some Alfisols), where the major chemical soil constraint is low P content/availability rather than soil acidity itself.