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The 7th Dr. B.V. Mehta Memorial Lecture*

Iron Toxicity in Wetland Rice: Occurrence and Management through Integration of Genetic Tolerance with Plant Nutrition

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Abstract: Iron toxicity is caused by excess iron mobilized in soil solution under submerged conditions in wetland rice. Iron toxicity is common in the humid zones of tropical regions on acid sulfate soils, acid Ultisols, Oxisols and sandy soils with a low cation exchange capacity, moderate to high acidity and easily reducible iron and low to moderately high in organic matter. Iron toxicity is reported to reduce rice yields by 12-100%, depending on the intensity of the disorder, iron-tolerance of the genotype, soil fertility, and soil, water and nutrient management practices. In this memorial lecture I share my research experiences and recent literature, with examples, on the occurrence of iron toxicity and its management through an integrated use of iron-tolerant rice genotypes with balanced nutrient management. It is concluded that the integrated approach has the potential to increase rice production on iron-toxic soils in tropical regions. ***(Key words:** Iron toxicity, occurrence, tolerance to iron, role of other nutrients, integrated approach)*

It is an honour and a privilege to have this opportunity to address the members of the Hyderabad Chapter of the Indian Society of Soil Science on the occasion of the seventh Dr. B.V. Mehta memorial lecture. I am really pleased to be amidst many colleagues and research partners at ANGRAU (Acharya N.G. Ranga Agricultural University, Rajendranagar, Hyderabad) of long standing.

The late Dr. B.V. Mehta made a significant contribution to soil fertility research in general and micronutrient research in particular. I take this opportunity to pay my humble homage to Dr. Mehta. For this lecture I have chosen the topic "Iron toxicity in wetland rice: occurrence and management through integration of genetic tolerance with plant nutrition". The topic is of much significance for wetland rice growing, production and productivity in the traditional humid and sub-humid tropical regions of India and globally. The importance of rice as a staple food globally cannot be overemphasized.

Why Iron Toxicity?

There has been a relatively greater research effort and the information generated on iron deficiency or iron chlorosis of crops is far larger than on iron toxicity. This is due to the fact that not only iron chlorosis is more widespread globally but also perhaps more importantly, it affects the production of food and fruit crops in both the developed and developing world. On the other hand, iron toxicity is a nutrient disorder that is largely confined to the tropical world and affects the growing of wetland rice crop in the humid and sub-humid zones. Relatively less research has been done on iron toxicity globally.

I, therefore, thought it more interesting to share my experiences and recent literature on iron toxicity of wetland rice. The lecture covers the aspects relating to the occurrence and management of iron toxicity in wetland rice. The topic is of scientific and practical importance. Firstly, iron toxicity disorder of rice would seem equally complex and intriguing as iron chlorosis is. Secondly, I have been personally involved and am aware of the recent research on iron toxicity in wetland rice in both tropical Asia and West Africa. In West Africa, a large area under inland valleys, suitable for wetland rice cultivation, remains unexploited (Andriesse and Fresco 1991). Iron toxicity is widespread and is a major constraint to the utilization of inland valley swamps for increasing rice production and productivity (Sahrawat *et al.* 1996;

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Sahrawat and Singh 1997; Sahrawat 1998). Thirdly, recent research has shown that iron toxicity in wetland rice can be reduced through an integrated use of genetic tolerance and soil and water and nutrient management. Fourthly, the integrated approach for reducing iron toxicity in wetland rice is economical and practically more feasible (than use of genetic tolerance or natural resource management alone) and can provide a sustainable increase in rice productivity of wetland soils where iron toxicity is present. The underlying principles of such an approach foi combating iron toxicity in rice have far wider application for boosting rice production in tropical wetlands where iron toxicity is present.

The research on iron toxicity occurrence and management in wetland rice has largely been conducted by researchers who have had the opportunity to work in tropical regions in Asia, Africa and Latin America, where iron toxicity is present and is a major constraint to wetland rice production. It is therefore not surprising to find out in various international meetings or symposia on iron nutrition of crops that researchers largely cover research topics relating to iron chlorosis or deficiency and indeed very few papers deal with the aspect of iron nutrition relating to iron toxicity.

Iron as a plant nutrient has some intriguing but interesting chemistry as iron deficiency and toxicity could occur simultaneously. For example, in West Africa rice is grown along the toposequence in inland valleys rather than in idealized rice paddies as in Asia. Under undulating topography, the pool of reducible iron is depleted by leaching of the ferrous iron from upper slopes and hydromporphic zones (between upland and inland swamp) of the toposequence. Consequently, the level of reducible iron in the soil drops to low values and the upland rice grown in the upland or hydromorphic zone of the toposequence is affected by iron deficiency. On the other hand, the inflow of ferrous iron from the upperslopes (upland plus transition zones of the toposequence) results in accumulation of iron in the valley bottom or inland swamp part of the inland valley system, resulting in iron toxicity to wetland rice grown in the inland swamps. Thus, the disorder relating to iron "from deficiency to toxicity" indeed can occur simultaneously at a site along a toposequence under undulating topography as observed in the humid zones of West Africa (K. L. Sahrawat, unpublished observations).

Historical

Wetland rice has been reported to suffer from the "bronzing", "yellowing" or related diseases in many states in the country including Orissa, Bihar, Madhya Pradesh and Bengal since a long time (Sahu 1968). Bronzing disease of wetland rice has also been reported under various local names in the rice growing areas of the world. In India, the first report by E.J. Woodhouse in 1913 on the bronzing disease of rice was from rice growing in wetlands in Champaran , Darbhanga, Muzaffarpur and Sahabad districts of Bihar and in Sambalpur district of Orissa. In the same year (1913), E.J. Hector reported the occurrence of bronzing disease of rice in Bengal. Several reports of the disorder followed from many locations in the states of Orissa and Madhya Pradesh (Sahu 1968).

Sahu (1968) made detailed study of the occurrence of bronzing disease of rice in the wetlands of Orissa and reported that excess iron or iron toxicity, sulfide injury or manganese toxicity at various sites caused bronzing and related disease. Bronzing disease of lowland rice has also been reported as a constraint to rice yields and is a common occurrence in the northwest Himalayan regions. A survey of the rice paddies showed that about 42% of wetland rice showed bronzing symptoms (Verma and Tripathi 1989; Verma 1991).

Iron toxicity commonly occurs in acid sulphate and acid Ultisols and Oxisols that are rich in reducible iron. In Sri Lanka, the symptoms of oranging or bronzing observed in rice growing on strongly acid soils were attributed to excess iron or iron toxicity by Ponnamperuma *et al.* (1955). Since this first report, the disorder has been reported from several rice growing countries including Brazil, China, Colombia, India, Indonesia, Malaysia, the Philippines, Sri Lanka, Vietnam and throughout the West African region (Sahu 1968; Tanaka and Yoshida 1970; Haque 1977; Virmani 1977; van Breemen and Moormann 1978; Ikehashi and Ponnamperuma 1978; Yoshida 1981; Li and Ponnamperuma 1984; Fageria and Rabelo 1987; Abifarin 1988; Jugsujinda and Patrick 1993; Genon *et al.* 1994; Sarwani *et al.* 1995; Sahrawat *et al.* 1996; Sahrawat and Singh 1997; Olaleye *et al.* 2001).

The nutritional disorder of wetland rice known as Akagare Type 1 in Japan and bronzing in Sri Lanka were attributed to iron toxicity (Ponnamperuma *et al.* 1955; Yoshida and Tanaka 1970). The nutritional disorder known as Akiochi in Korea is also attributed to iron toxicity (Park and Tanaka 1968).

General Conditions for the Occurrence of Iron Toxicity in Submerged Rice Soils

Iron toxicity is an important nutrient disorder of wetland rice grown on acid sulphate soils, Ultisols, Oxisols and light-textured sandy soils, with moderate to high acidity and active (easily reducible in submerged soils) iron, low cation exchange capacity and low to moderately high in organic matter (Ponnamperuma 1972; Moormann and van Breemen 1978; Narteh and Sahrawat 1999). Iron toxicity is a disorder caused when an excessive amount of Fe (II) is mobilized *in-situ* in solution or when interflow brings Fe (II) ions to valley bottoms in inland valleys.

The occurrence of iron toxicity is associated with a high concentration of Fe (II) in soil solution (Ponnamperuma *et al.* 1955). This disorder exclusively occurs under submerged or anaerobic soil conditions because the amount of soluble iron in aerobic soils is negligible. Ponnamperuma (1976) listed seven important criteria for the occurrence of iron toxicity in rice in submerged soils:

- The pH of the air- dry soil, less than 6.5.
- High reactivity (reducibility) and content of Fe (III) oxide hydrates.
- High reserve acidity.
- Low percolation rate in the soil.
- High interflow of Fe (II) from the adjacent areas.
- Temperature, low temperature brings late but high and persistent concentrations of water- soluble iron.
- Salt content, salts increase iron concentration in soil solution.

Iron toxicity in inland swamps associated with the interflow of ferrous iron is especially important in areas where land has undulating topography and rice is grown along the toposequence rather than in the rice paddies (Sahrawat 1994). Under these conditions, the hydrology and the interflow of iron from upper slopes to foot-slopes and to valley bottoms in the inland valley is a common feature, and is often the cause of iron toxicity occurrence in rice grown in the valley bottoms and at times in the hydromorphic zone (between upland and inland swamp) of the continuum or toposequence (Sahrawat 1994, 1998).

Iron toxicity affects wetland rice grown under irrigated lowland or rainfed lowland conditions when the soil is reduced and Fe (II) is formed or transported in toxic concentrations. Iron toxicity has been reported to reduce lowland rice yields by 12-100% depending on the intensity of iron toxicity and tolerance of the rice cultivar (Sahrawat *et al.* 1996).

Iron toxicity symptoms vary with rice varieties and are characterized by a reddish brown, purple bronzing, yellow or orange discolouration of the lower leaves of the rice plants. Typically, iron toxicity symptoms are generally manifested as tiny brown spots starting from the tips and spreading towards the bases of the leaves of the lower leaves of the rice plants. The brown spots coalesce on the interveins of the leaves with progressing Fe toxicity. With increased iron toxicity, the entire leaf looks purplish brown followed by drying of the leaves, which gives the rice plant a scorched appearance (Sahrawat *et al.* 1996). Iron toxicity symptoms in the rice plant in rice paddies commonly develop at maximum tillering and heading stage of the rice plant, but the toxicity symptoms may be observed at any growth stage. The roots of the rice plants affected by iron toxicity disorder become scanty, coarse and blunted, and dark brown in colour. With the alleviation of the iron toxicity the roots may recover to the usual white colour.

Table 1. The range of oxidation-reduction potential encountered in rice soils ranging from well drained to submerged conditions

Soil water condition	Redox potential (mV)
Aerated or well-drained	+700 to +500
Moderately reduced	+400 to +200
Reduced	+100 to -100
Highly reduced	-100 to -300

Source: Patrick and Reddy (1978)

Soils on which rice is grown experience a range of redox potential (Eh) depending on the moisture regime (well drained to submerged) and organic matter status of the soil (Table 1). The data can provide a useful guideline for classifying soil reduction in diverse soil conditions under which rice is grown (Patrick and Reddy 1978). Since Fe (III) reduction occurs in reduced soils, the occurrence of iron toxicity in wetland rice is greatly influenced by soil reduction or Eh. The concentration of Fe (II) in soil solution increases following flooding due to reduction of Fe (III) oxide by iron reducing bacteria oxidizing organic matter. The reduction of Fe (III) to Fe (II) takes place at an Eh of 150-180 mV.

A rapid increase in Fe (II) following flooding of soils is favoured by low initial soil pH, presence of easily reducible Fe, a sustained supply of organic matter, a high fertility status of the soil and the absence of the compounds with a higher oxidation state than Fe (III) oxide especially, oxygen and Mn (III, IV) oxide and nitrate in the soil (Table 2) that serve as electron acceptors in the absence of free oxygen (Ponnamperuma 1972; Sahrawat 1998; Narteh and Sahrawat 1999).

The reduction of Fe (III) to Fe (II) can be represented by the following equation (equation 1) in which Fe oxide serves as the source of reducible Fe and electron acceptor and organic matter (CH_2O) serves as the electron donor:

Table 2. Range of redox potentials in which the main oxidized components in submerged soils become unstable

Reaction	Redox potential (mV)
$O_2 - H_2O$	+ 380 to + 320
$NO_3 - N_2$, Mn^{4+} - Mn^{2+}	+ 280 to + 220
Fe^{3+}_2 - Fe^{2+}	+ 180 to + 150
SO_4^{2-} - S^{2-}	- 120 to – 180
$CO_2 - CH_4$	- 200 to – 280

Source: Patrick and Reddy (1978)

$$Fe_2O_3 + ½ CH_2O + 4 H^+ = 2 Fe^{2+} + 5/2 H_2O + ½ CO_2 \quad ...(1)$$

The forms of Fe that are important in redox reactions are largely mixtures of X-ray amorphous materials and geothite mineral of variable but low water solubility. Amorphous Fe oxide is more easily reducible by bacterial activity than the crystalline Fe oxides (Munch and Ottow 1980; Wahid and Kamalam 1993; Olaleye *et al.* 2000).

Based on the study of Asian wetland rice soils, Ponnamperuma (1978) suggested that the increase in concentration of water-soluble iron following submerging of soils could be described for most mineral soils by the following equation:

$$Eh = 1.06 – 0.059 \log Fe^{2+} - 0.177 pH \quad ...(2)$$

Narteh and Sahrawat (1999) the influence of flooding on while studying electrochemical and chemical properties of 15 rice soils from West Africa, found that at 4 weeks after flooding, the soil solution redox potential (Eh in mV) could be predicted from the concentration of Fe (II) (mg L^{-1}) in soil solution and soil solution pH by the equation:

$$Eh = 409 – 4.09 \log Fe^{2+} - 59 pH; R^2 = 0.99 \quad ...(3)$$

It was further revealed that the changes in soil solution pH corresponded to changes in soil solution Eh. A dynamic stability in Eh-pH relationship was recorded at 4 weeks after flooding of the soils (R^2 =0.84, n = 15) (Narteh and Sahrawat 1999).

Level of iron in the Growing Medium and in Plant

Iron toxicity has been reported to occur at a wide range of iron concentration in the culture solution, varying from as low as 10 mg Fe L^{-1} to 1680 mg Fe L^{-1} or higher (De and Mandal 1957;Tanaka *et al.* 1966; Bode *et al.* 1995; Narteh and Sahrawat 1999).

A study of the kinetics of Fe (II) release under submerged condition in an iron-toxic Ultisol from the humid savanna zone in Korhogo, Ivory Coast (West Africa) showed that the concentration of Fe (II) in soil solution varied from 50 to 150 mg L^{-1} during 3-10 weeks after flooding of the soil in greenhouse pots (Narteh and Sahrawat 1999). In field experiments, rice plants growing on the Ultisol showed severe iron toxicity symptoms. The results suggested that Fe (II) concentrations in soil solution in the range of 50-150 mg L^{-1} caused iron toxicity to rice in this soil in Korhogo, Ivory Coast. The results further showed that on this gently sloping site, the contribution of ferrous iron through interflow was low and less important than the release of ferrous iron *in-situ* in causing iron toxicity to wetland rice (Sahrawat and Sika 2002; Sahrawat *et al.* 2001).

In addition to concentration of Fe (II) in soil solution, the occurrence of iron toxicity can be influenced by reduction products such as sulphides and organic acids. The critical concentration of Fe (II) in the growing medium for the development of iron toxicity symptoms may vary depending largely on the nutrient status of the plant and the presence of reduction products. In the absence of harmful levels of reduction products such as sulphides and organic acids and an adequate supply of plant nutrients, the rice plants suffer from iron toxicity at Fe (II) concentrations greater than 300-500 mg L^{-1} (van Breemen and Moormann 1978).

Verma (1991) showed that the critical concentration of iron in rice plant samples collected from various growing sites in northwest Himalayas that caused iron toxicity in rice at the flowering stage of growth, varied from 650 to 775 mg Fe kg^{-1} of dry tissue. These results on iron concentration in plant tissue in the occurrence of iron toxicity in wetland rice complement those relating to the concentration of iron in the growing media. They clearly suggest that there is a wide range of iron concentration that causes iron toxicity to rice growing on iron toxic soils or in culture solution.

Field studies made in West Africa on the effects of iron toxicity on the elemental composition of rice plants at tillering stage of iron-tolerant (iron toxicity-tolerant) and susceptible varieties grown under irrigated conditions showed that there were no differences in elemental composition relative to major and micronutrients except for iron. Both iron- tolerant and susceptible varieties had a high concentration of total iron, well above the critical limit of 300 mg Fe kg^{-1} plant dry wt. All other nutrient element concentrations were adequate in the plant tissue. The results suggest that iron toxicity studied in the field in West Africa is single nutrient (Fe) toxicity and not a multiple nutrient deficiency stress (Sahrawat *et al.* 1996; Sahrawat 2000).

Selected data on chemical characteristics of the iron-toxic Ultisol in Korhogo, in the humid savanna

Table 3. Chemical characteristics of an iron-toxic Ultisol at Korhogo, Ivory Coast (West Africa), in 1997

Soil characteristic	Value
pH (water)	5.4
pH (1 M KCl)	4.0
Organic C (g kg^{-1})	11.2
Bray 1 extractable P (mg kg^{-1})	9
Exchangeable cations (cmol kg^{-1})	
K	0.08
Mg	0.29
Ca	0.83
CEC (cmol kg^{-1})	12.2
DTPA extractable Fe (mg kg^{-1})	490
DTPA extractable Zn (mg kg^{-1})	4

Source: Sahrawat (2000)

Table 4. Macro- and micronutrient content (mg kg^{-1}) in plant tops of iron- tolerant (CK4) and susceptible (Bouake189) varieties without (0) and with (+ NPKZn) treatments at 60 days after transplanting at Korhogo, Ivory Coast, in 1997

Nutrient Element	CK 4		Bouake 189	
	0	+ NPKZn	0	+ NPKZn
N	15,500	16,600	13,600	14,800
P	2,800	3,200	3,000	3,300
K	18,600	22,500	24,600	23,400
Ca	2,000	2,300	2,000	2,000
Mg	1,100	1,200	1,200	1,200
Fe	2,060	1,459	1,607	1,622
Mn	224	226	164	201
Zn	34	37	37	38

Source: Sahrawat (2000)
The experiment was conducted under irrigated condition. Under+NPKZn treatment, rice crop received 100 kg N ha^{-1} as urea in three splits, 50 kg P ha^{-1} as triple superphosphate, 80 kg K ha^{-1} as potassium chloride and 10 kg Zn ha^{-1} as zinc sulphate. The applications of P, K and Zn were made as basal.

zone of Ivory coast (West Africa) and elemental composition of the plants for major and micronutrients at tillering stage of plant growth of iron-tolerant and susceptible varieties are given in Tables 3 and 4. It is clear that the soil had high reserve acidity (indicated by pH in KCl) and high concentration of extractable Fe. The soil had relatively low cation exchange capacity and was low in exchangeable K, moderate in organic C and available Zn and low in available P (Table 3). The plant tops at 60 days after transplanting contained high concentration of iron in both control (0, no nutrients applied) and treatment (N, P, K and Zn added, + NPKZn) plots. The levels of other nutrients in the plant tops were generally similar and seemed adequate in both 0 and + NPKZn treatments (Table 4).

Since the severity of iron toxicity in wetland rice depends on several environmental factors, it is difficult to correlate the iron status of the rice plant with iron content in the growing medium. In view of a wide range in reported concentrations of iron in soil solution that cause iron toxicity to rice, it is indicated that there seems to be no simple or direct relationship between iron concentration and the occurrence of iron toxicity. Iron toxicity occurrence and its severity also depend on the genotype (especially its tolerance to excess iron), seasonal weather (especially temperature) nutrient status of the soil, and water and soil management practices (Sahrawat *et al.* 1996; Sahrawat and Singh 1998; Audebert and Sahrawat 2000).

Tolerant Genotypes and Plant Nutrient Management for Reducing Iron Toxicity

Several cultural practices such as pre-submergence of the field (soil), water management and ridge planting can be manipulated for reducing iron toxicity in wetland rice (Sahrawat 1979; Abu *et al.* 1989; Winslow *et al.* 1989; Baggie and Bah 2001). However, the most cost-effective approach, especially for the resource poor farmers is the use of iron-toxicity tolerant (or iron-tolerant) rice varieties. Under high intensity of iron toxicity, a combination of iron-tolerant variety and improved soil, water, and nutrition management may give the best and sustainable results (Sahrawat *et al.* 1996; Audebert and Sahrawat 2000).

Iron toxicity of wetland rice is a physiological, complex nutrient disorder and the deficiencies of several other nutrients, especially P, K, Mg, Mn and Zn have been implicated to play a role in the occurrence of iron toxicity in wetland rice (Sahu 1968; Ottow *et al.* 1983; Yamauchi 1989; Sahrawat *et al.* 1996; Sahu 2001). Deficiencies of nutrients such as Ca, Mg and Mn are rarely observed in lowland rice, the deficiencies of P, K and Zn deserve special attention to reduce iron toxicity (Sahrawat *et al.* 1996).

For sustainable management of iron toxicity in lowland rice, an integrated approach in which the use of iron-tolerant rice varieties, soil and water management and plant nutrition are combined, is most appropriate. It has been observed that under conditions of iron toxicity in lowland rice the requirements for other nutrients is increased for maintaining a healthy and normal growth of the rice plants (Sahrawat *et al.* 1996). Hence the applications of other nutrients, especially P, K and Zn along with N are needed to overcome the physiological disorder.

Sahrawat *et al.* (2000) conducted field experiments at two sites in Mbe and Korhogo, Ivory Coast from 1992 to 1997 to evaluate the performance of promising rice cultivars for their tolerance to iron toxicity in lowland soils. Soils of the two sites differed markedly in iron toxicity. High intensity of iron toxicity at Korhogo site and little or no iron toxicity at Mbe during 1992, 1993 and 1994 seasons provided data, which were used to estimate yield loss due to iron toxicity in selected iron-tolerant and susceptible rice cultivars. The differences in yield at Mbe and Korhogo varied from 0.41 to 3.53 t ha^{-1} resulting in yield reductions varying from 9 to 49 per cent (Sahrawat *et al.* 2000). The reduction in yield was affected by iron toxicity-tolerance, which varied with genotype and season (Sahrawat and Singh 1998; Audebert and Sahrawat 2000).

Sahrawat *et al.* (1996) evaluated the performance of 20 rice cultivars in the wet season under irrigated condition at an iron-toxic site on an Ultisol in Korhogo, Ivory coast. The cultivars received uniform application of N (100 kg ha^{-1}), P (50 kg ha^{-1}), K (80 kg K ha^{-1}) and Zn (10 kg ha^{-1}). The grain yields of the cultivars varied from 0 to 5.04 t ha^{-1}. The iron toxicity scores based on the extent of toxicity symptoms (bronzing) expressed on the foliage, using a scale of 1-9, varied from 2 to 9. In this evaluation scheme, a score of 1 indicates normal growth and 9 indicates that almost all plants were dead or dying (IRRI 1988). Of the 20 cultivars grown in 1992, all the five upland cultivars evaluated showed little tolerance to iron toxicity as they gave almost zero grain yield. The grain yields of the other 15 rice cultivars showed a wide range and varied from 2.76 to 5.04 t ha^{-1}.

Evaluation of lowland rice cultivars for iron toxicity tolerance during five years (1992-1997) at the iron-toxic site at Korhogo (Table 5), showed that among the three promising iron toxicity-tolerant cultivars, CK 4 was the top yielder and gave an average grain yield of 5.33 t ha^{-1}, followed by WITA 1 (average grain yield of 4.96 t ha^{-1}) and Suakoko 8 (3.80 t ha^{-1}). These results show that lowland rice varieties with superior iron tolerance combined with balanced plant nutrition can bring a sustainable increase in rice yields on iron toxic soils (Sahrawat 2000).

In an experiment conducted for four years (1995-1998), Sahrawat *et al.* (2001) evaluated the performance of one iron toxicity- tolerant and two susceptible rice cultivars at the iron-toxic site in Korhogo. Results showed that, without the application of nutrients, iron toxicity-tolerant CK 4 outyielded susceptible cultivars Bouake 189 and TOX 3069-66-2-1-6. With the application of N + P + K + Zn, grain yields of all three cultivars increased significantly, ranging from 4.7 to 5.7 t ha^{-1} (Table 6). The increase in grain yields of iron toxicity-susceptible Bouake 189 and TOX 3069-66-2-1-6 was more than that of iron toxicity-tolerant CK 4. Iron toxicity scores based on expression of normal symptoms were generally lower in treatments where plant nutrients were added than in treatments without fertilizer. Applying a combination of N + P + K + Zn resulted in the lowest iron toxicity score. The results indicated that the application of other plant nutrients reduced iron toxicity and increased grain yields (Table 6). From these results, it was concluded that grain yield on iron-toxic soils can be improved by applying nutrients. A combination of genetic tolerance with nutrients gave better yield (Table 6).

Perspectives

Recent research has established the conditions that lead to the occurrence of iron toxicity in wetland rice. Iron toxicity occurs in soils with high reducible iron and potential soil acidity, irrespective of organic matter and texture of the soil, although the concentration of iron in the medium to cause iron toxicity varies with soil characteristics including organic matter and texture. Iron toxicity is caused by excess iron in soil solution in reduced soils and aggravated by low base status and the deficiencies of other plant nutrients such as P, K and Zn. Iron toxicity can be reduced

Table 5. Performance of lowland rice cultivars WITA 1 and WITA 3 during 1992-1997 as evaluated by grain yield (t ha^{-1}) relative to the performance of iron toxicity-tolerant (Suakoko 8 and CK 4) and iron toxicity-susceptible (Bouake 189) check cultivars under irrigated conditions in the wet season at an iron-toxic site in Korhogo, Ivory Coast

Year	CK 4	WITA 1	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	

Source: Sahrawat *et al.* (2000)
Each season, all cultivars received uniform application of 100 kg N ha^{-1}, 50 kg P ha^{-1}, 80 kg K ha^{-1} and 10 Zn ha^{-1} in plots measuring 12 m^2 in 1992-1994 and 24 m^2 in 1996-1997.

Table 6. Effects of field applications of nutrients on grain yield of iron toxicity-tolerant CK 4 and susceptible Bouake 189 and TOX 3069-66-2-1-6 lowland rice cultivars grown on an iron-toxic soil in Korhogo, Ivory Coast (1995-1998)

Treatment	Grain yield (t ha^{-1})		
	CK 4	Bouake 189	TOX 3069-66-2-1-6
No fertilizer	4.3 (3)[a]	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

Source: Sahrawat *et al.* (2001)
[a]Iron toxicity scores are given in parentheses. The data presented are average of four years (1995-1998). All cultivars received uniform application of N (100 kg ha^{-1}), P (50 kg ha^{-1}), K (80 kg ha^{-1}) and Zn (10 kg ha^{-1}).

by growing lowland rice cultivars with tolerance to excess iron or iron toxicity and by the application of nutrients such as P, K and Zn whose requirement for rice plant is increased under iron toxicity.

The interaction between iron toxicity and the availability of plant nutrients such as P, K and Zn and others is poorly understood and there is a need for future research to establish these interactions in the occurrence of and tolerance to iron toxicity and its management.

A synergy between genetic tolerance to iron toxicity and nutrient management strategy is crucial for sustainable rice production and productivity on iron-toxic soils. An intensified use of iron-toxic soils is unavoidable in the face of an effort for meeting the food needs of ever-growing population in the tropical regions where iron toxic soils are important natural resource for food production.

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