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The role of tolerant genotypes and plant nutrients in the management of iron toxicity in lowland rice

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SUMMARY

Iron toxicity is a nutrient disorder associated with high concentrations of iron in soil solutions Deficiencies of other nutrients, such as P, K, Ca, Mg and Zn, have been implicated in its occurrence in rice plants Field experiments were carried out in 1992 and 1993 in Ivory Coast to evaluate the iron toxicity tolerance of promising rice cultivars available in West Africa, and to provide additional information for selecting breeding materials Two sites, differing in their potential to cause iron toxicity, were used Glasshouse and field studies were also conducted to test the role of other nutrients in the occurrence of iron toxicity The results showed that genetic tolerance to iron toxicity can significantly improve rice production in iron-toxic soils, with some cultivars producing yields in excess of 5 t/ha The application of N, P, K and Zn in the field decreased the uptake of iron in rice tops, and this can be a significant factor in the iron-toxicity tolerance of the cultivars

INTRODUCTION

Iron toxicity is a widespread nutrient disorder affecting rice growing in inland swamps and on the irrigated lowland soils of West Africa (Abifarin 1988, Ottow *et al* 1991) Iron toxicity occurs when large amounts of iron are mobilized in soil solution or when an inflow of iron occurs from upper slopes (Ponnamperuma 1972, Moormann & van Breemen 1978) The occurrence of iron toxicity is associated with a high concentration of ferrous ions in soil solution (Ponnamperuma *et al* 1955) It is also known that a high concentration of iron in solution decreases the absorption of other nutrients, especially P and K, by the rice plant (Yoshida 1981)

Iron toxicity in West Africa has been reported to reduce rice yields by 12–100% depending on the intensity of toxicity and the tolerance of the rice cultivar (Masajo *et al* 1986, Abifarin 1988, 1989) Cultural factors such as planting date, ridge planting, water management and pre-submergence of soil can be manipulated to reduce iron toxicity in rice (Ponnamperuma 1977, Sahrawat 1979, Abu *et al* 1989, Winslow *et al* 1989) The most cost-effective approach is the use of iron-tolerant rice cultivars (Abifarin 1989) Under extreme iron toxicity a combination of tolerant cultivar and improved cultural practices may give the best results

Iron toxicity is a complex nutrient disorder and deficiencies of other nutrients, especially P, K, Ca, Mg and Zn, have been considered to affect its incidence in rice (Tanaka *et al* 1966, Ottow *et al* 1983, Yamauchi 1989) These other nutrients may play an important role not only in the management of iron toxicity but also in the expression of iron tolerance by different cultivars

Based on available information, iron toxicity cannot be eliminated entirely by improving the nutritional status of the plant Deficiencies of nutrients such as P, K, Ca, Mg and Mn are known to decrease the iron-excluding power of rice roots and can thus affect the rice plant's tolerance to iron toxicity (Yoshida 1981) Deficiencies of Ca, Mg and Mn are rarely observed on lowland rice and therefore P and K deficiencies probably deserve special attention

Field experiments were carried out in 1992 and 1993 to evaluate the iron tolerance of promising rice cultivars available in West Africa, and to provide additional information for selecting breeding materials Glasshouse and field studies were also conducted to test the role of other nutrients in causing iron toxicity It is believed that an integrated approach, in which genetic tolerance, soil management and plant nutrition are combined, is most appropriate for the sustainable management of iron toxicity

MATERIALS AND METHODS

Field experiments

Four field experiments were conducted under irrigated conditions at Mbe and Korhogo in Ivory Coast in 1992 and 1993 to evaluate promising rice cultivars for their tolerance to iron toxicity in lowland soils. Mbe represents a transition between the forest and savanna zones while Korhogo is located in the savanna zone.

Soils

The soil at Mbe is an Alfisol with sandy clay loam texture, and the soil at Korhogo is an Ultisol with sandy loam texture (Table 1). Soil samples were taken before initiating the experiment, air-dried, ground and sieved through a 2 mm screen before analysis. Soil pH was measured by a glass electrode using a soil: water or salt solution ratio of 1:2·5. Organic C was determined as described by Walkley & Black (1934). Total P content in soil samples was determined by digestion with perchloric acid and extractable P was determined using NH_4F-HCl solution (Bray 1), using a soil: extractant ratio of 1:7 (Olsen & Sommers 1982). Exchangeable cations were determined using 1 N neutral ammonium acetate and the cations in the extract determined by atomic absorption spectrophotometry. Extractable Fe and other micronutrient elements were determined by extracting the soil samples with DTPA (Lindsay & Norvell 1978).

In 1992, 20 cultivars were evaluated, including five upland cultivars which had shown good performance in acidic upland soils. Based on the 1992 results, 12 cultivars were further tested at these two sites in 1993.

In both years a randomized complete block design was used with four replications. In 1992, the plot size was 12 m^2 at both sites, while in 1993 the plot size was 12 m^2 at Mbe and 24 m^2 at Korhogo. All plots received a basal application of 200 kg/ha of 10:18:18 (N:P:K). A total of 100 kg N/ha was applied uniformly to all plots, 20 kg through the basal application of N:P:K fertilizer and the remaining 80 kg of N as urea top-dressed at the tillering and panicle initiation stages of the rice crop. Seedlings (3–4 weeks old) were transplanted to the rice paddies using a spacing of 25 × 25 cm.

Table 1. *Chemical characteristics of the soils at Mbe and Korhogo* (*Ivory Coast*) *used for evaluating promising rice cultivars for iron-toxicity tolerance in 1992 and 1993, and of the Mbe soil used in the pot experiment*

	Mbe	Korhogo	Pot experiment
pH (H_2O)	6·2	5·9	6·2
pH (KCl)	4·7	4·1	4·7
Organic C (%)	1·87	1·02	0·87
Total P (mg/kg)	226	192	—
Extractable nutrients (mg/kg)			
Bray 1			
P	4	8	15
K	70	55	41
Ca	325	310	304
Mg	68	64	65
Fe	89	137	77
Zn	3	7	0·2

To test the role of other nutrients in iron toxicity, another field experiment was conducted during the 1993 rainy season at an iron-toxic site at Korhogo. The two cultivars tested were Suakoko 8, a tolerant cultivar, and Bouake 189, a susceptible cultivar. The effects of nine nutrient treatments (no fertilizer, N, N+P, N+K, N+Zn, N+P+Zn, N+K+Zn, N+P+K, N+P+K+Zn) were tested in a randomized complete block design with four replications. Nitrogen was applied at a rate of 100 kg N/ha as urea in three splits; P was applied at 50 kg P/ha as triple superphosphate; K at 80 kg/ha as potassium chloride (KCl); and Zn at 10 kg Zn/ha as zinc oxide (ZnO). All nutrients except N were added as basal applications. Plot size was 24 m^2.

Plants were visually scored for iron toxicity symptoms, using a scale of 1–9 based on the IRRI standard evaluation system for rice. A score of 1 indicates normal growth and tillering and 9 indicates that almost all plants were dead or dying (IRRI 1988). The plants were scored two or three times during the growth period when iron toxicity symptoms were expressed on the foliage. The iron toxicity scores were made on all plots and final score is a mean of all observations made.

Plant samples were also collected at the tillering stage from the field experiment at Korhogo, where the effects of other nutrients on iron toxicity were studied. Plant samples from no fertilizer, and N+P+K+Zn treatments were analysed for macro- and micronutrient elements at the Wetland Biogeochemistry Institute, Louisiana State University, using methods similar to those described by Jones *et al.* (1991) with a Thermal Jarrell Ash Inductively Coupled Argon Plasma Spectrophotometer (ICP 61).

Pot experiment

The soil used in the pot experiment was from the Mbe valley. During the 1991 season, severe iron toxicity symptoms were observed on rice growing in the field in this soil. Bouake 189 was observed to be one of the lowland rice cultivars most susceptible to iron toxicity and this cultivar, together with an *Oryza glaberrima* cultivar (CG 14), were tested for their relative tolerance to iron toxicity with different nutrient treatments. *O. glaberrima* is known to be tolerant to iron. The experiment was conducted during March–July 1992 in pots in a glasshouse at ambient temperature. Soil analysis was conducted as described in Table 1. There were five treatments consisting of control (no fertilizer), P (10 mg P/kg soil as triple superphosphate), K (60 mg K/kg soil as potassium chloride), Zn (5 mg Zn/kg soil as zinc sulphate) and P+K+Zn (at the specified rates). All treatments received a uniform application of N (100 mg N/kg soil as ammonium sulphate) applied at planting, tillering and flowering. All other nutrients were added at planting.

The pots, holding 2 kg soil, were saturated with water (no free water) and 5 seeds/pot were sown in four replications of each treatment. The seedlings were thinned to 3 plants/pot once they were established. The soil in the pots was kept submerged under a 2–3 cm layer of water throughout the growing period. The progressive development of iron toxicity symptoms was observed and the grain and straw weights were determined at harvest.

All data were subjected to analyses of variance.

RESULTS AND DISCUSSION

Evaluating promising rice cultivars

Soils of the sites at Mbe and Korhogo differed markedly in iron toxicity (as shown by iron toxicity scores of the standard susceptible and tolerant rice cultivars) in the 1992 growing season. The iron toxicity score (IRRI 1988) for the standard tolerant control, Suakoko 8, was consistently high (3) at Korhogo and low (1) at Mbe. Soil acidity, as measured by soil pH in water and KCl on air-dried soil samples, was higher at Korhogo than at Mbe, as was the amount of extractable iron (Table 1).

Iron toxicity symptoms observed in the field experiments varied with cultivar but were typically manifested as tiny brown spots on the lower leaves starting from the tips and spreading toward the bases of the leaves. These spots coalesced on the interveins. With increased iron toxicity, the entire leaf seemed purplish brown.

Of the 20 cultivars grown at the two sites in 1992, all the upland cultivars showed little tolerance to iron toxicity at Korhogo as shown by their grain yield, and their yields at the Mbe site were also relatively low, reflecting poor adaptation to flooded conditions (Table 2). Suakoko 8 (tolerant) gave a lower grain yield at Mbe than at Korhogo and lodged badly at Mbe, whereas plant height was reduced at Korhogo. The performance of the local susceptible control, Bouake 189, reflected its ability to take advantage of the low-iron toxic conditions prevailing at Mbe during the 1992 season. Another control cultivar, ITA247, appeared to be relatively tolerant to iron toxicity

Table 2. *Performance of 20 rice cultivars at a site with high iron toxicity (Korhogo) and a site with low iron toxicity (Mbe), Ivory Coast in 1992*

Cultivar	Grain yield (t/ha) Korhogo	Grain yield (t/ha) Mbe	Iron toxicity score at Korhogo
Lowland			
TOX 3100-32-2-1-3-5	5.04	6.35	2
TOX 3107-39-1-2-1	5.00	5.65	2
Suakoko 8 (control)	4.85	4.44	3
ITA 408	4.42	6.49	3
ITA 247 (control)	4.37	4.68	3
TOX 3118-6-E2-3-2	4.33	5.72	3
TOX 3081-36-2-3-1	4.33	5.54	3
TOX 3027-43-1-E3-1-1-1	4.26	5.79	3
TOX 3118-42-1-1	4.09	6.36	3
ITA 326	3.95	4.50	3
TOX 3050-46-E3-3-3-3	3.31	6.52	3
TOX 85C-C1-10-WAS	3.29	4.70	5
TOX 85C-C1-17-WAS	3.24	4.70	7
Bouake 189 (local control)	2.87	5.64	7
TOX 3052-46-3-3-1	2.76	5.96	5
Upland			
IDSA 10	< 0.10	3.80	9
IDSA 16	< 0.10	4.12	9
IRAT 144	< 0.10	3.60	9
ITA 120	< 0.10	5.90	9
ITA 257	< 0.10	3.64	9
S.E.	0.539	0.478	—
D.F.	57	57	—

Table 3. *Performance of 12 cultivars at a site with high iron toxicity (Korhogo) and a site with low iron toxicity (Mbe), Ivory Coast in 1993*

Cultivar	Grain yield (t/ha) Korhogo	Grain yield (t/ha) Mbe	Iron toxicity score at Korhogo
CK4	5·87	8·17	2
CK73	5·62	2·28*	3
TOX 3118-6-E2-3-2	5·53	3·45*	6
TOX 3027-43-1-E3-1-1-1	5·36	7·38	4
TOX 3050-46-E3-3-3-3	5·36	5·87	5
TOX 3081-36-2-3-1	5·22	7·43	5
TOX 3100-32-2-1-3-5	5·17	3·42*	6
ITA 326	5·13	4·45	6
Suakoko 8 (control)	5·07	5·28	5
ITA 408	5·06	5·52	6
ITA 247 (control)	4·22	3·15	7
Bouake 189 (local control)	4·08	5·30	8
S.E.	0·251	0·699	—
D.F.	33	33	—

* Severe bird damage.

Table 4. *Grain and straw yield (g/pot) of Bouake 189 and* O. glaberrima *CG14 rice cultivars grown on soil from Mbe, Ivory Coast, in 1992*

Treatment	Bouake 189 Grain	Bouake 189 Straw	*O. glaberrima* CG14 Grain	*O. glaberrima* CG14 Straw
Control	6·5	7·2	7·7	7·2
Control + P	8·9	9·1	8·7	8·8
Control + K	6·7	7·7	7·3	8·0
Control + Zn	8·8	9·3	7·5	7·0
Control + P + K + Zn	8·2	9·3	8·4	8·3
S.E.	0·83	0·69	0·43	0·52
D.F.	12	12	12	12

These results also show that some of the TOX lines (breeding crosses made at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria) may have promising iron tolerance. In contrast, the iron-tolerant control cultivar, Suakoko 8, may have a low yield potential and thus be suited for conditions of high iron toxicity only.

Twelve cultivars were further tested at the same two sites in 1993 (Table 3). The iron toxicity rating for the standard tolerant cultivar, Suakoko 8, was again high (5) at Korhogo and low (1) at Mbe. Of the cultivars tested in 1993, CK4 was the highest yielder both at Korhogo and Mbe, with a grain yield of 8·17 t/ha at Mbe (Table 3). As in the 1992 season, TOX lines performed well, with yields > 5 t/ha. Suakoko 8 gave similar grain yields at both Korhogo and Mbe, and lodged badly at the Mbe site.

The results of this 2-year study show a range in iron tolerance, with several cultivars giving rice grain yields > 5 t/ha under high toxicity stress.

The lack of a good relationship between the iron toxicity score (ITS; based on the extent of visual iron toxicity symptoms) and grain yield was clearly demonstrated by the results of the field experiments. A new index, termed relative iron toxicity score (RITS; defined as the ratio of ITS of a cultivar to the ITS of a tolerant control, such as Suakoko 8) is suggested in place of ITS for the field evaluation of iron toxicity. To obtain RITS, the ITS of each cultivar was therefore divided by the ITS of Suakoko 8 in each season.

Simple correlation and regression analysis of the grain yield data of all the cultivars tested at Korhogo in 1992 and 1993 (except for the five upland cultivars tested in 1992; see Tables 2 and 3) showed that grain yields of the cultivars were not significantly correlated with ITS but were significantly negatively correlated with RITS ($r = -0{\cdot}7329$, $n = 27$). RITS thus seems a better index for scoring for iron toxicity because it normalizes the iron toxicity scores. The relationships between grain yield and RITS were described by the following regression equation:

$$\text{Grain yield} = 6{\cdot}1 - 1{\cdot}4\ \text{RITS}$$

It would be interesting to evaluate RITS as an index of iron toxicity in the field at other locations.

The role of other nutrients in iron toxicity of rice

In the pot experiment examining the effect of nutrients on the grain yield of rice, it was observed that typical iron toxicity symptoms appeared on the rice plants in

Table 5. *Effects of field [illegible] Korhogo, Ivory Coast in 1993*

Treatment	Grain yield (t/ha) Suakoko 8	Grain yield (t/ha) Bouake 189	Iron toxicity score Suakoko 8	Iron toxicity score Bouake 189
Control (no fertilizer)	5·79	4·47	3	5
N	5·43	4·59	3	4
N+P	6·02	6·70	3	4
N+K	6·77	6·24	3	4
N+Zn	6·12	5·75	3	4
N+P+Zn	6·09	5·58	3	5
N+K+Zn	5·37	5·36	3	5
N+P+K	6·85	5·70	3	4
N+P+K+Zn	6·05	6·19	3	4
S.E.	0·239	0·413	—	—
D.F.	24	24	—	—

Table 6. *Nutrient content (mg/kg) in plant tops of iron-tolerant and susceptible rice cultivars without (0) and with (+NPKZn) fertilizer treatment, at tillering stage at Korhogo, Ivory Coast in 1993*

Nutrient element	Critical content	Bouake 189 0	Bouake 189 +NPKZn	Suakoko 8 0	Suakoko 8 +NPKZn
P	< 1000	3777	3760	2709	3011
K	< 10000	26153	33722	24699	34874
Ca	< 1500	4751	2828	5180	4700
Mg	< 900	962	1015	860	852
Fe	> 300*	900	500	704	516
Mn	< 20	298	145	472	394
Zn	< 10	31	33	29	39
Cu	< 5	18	6	6	6
Al	> 300*	186	272	395	328

* Critical limit for toxicity. Other values refer to critical limits for deficiencies of nutrients.

all the treatments 4–6 weeks after emergence. Bouake 189 was more susceptible than *O. glaberrima* CG14 to iron toxicity. The application of P, either alone or with other nutrients, delayed the appearance of the toxicity symptoms by 1–2 weeks but did not alleviate them. The soil was low in extractable Zn and K but adequate in extractable P (Table 1). None of the treatments significantly affected grain and dry matter (DM) production although the grain and DM yields were higher in the treatments in which P was added either alone or in combination with K and Zn (Table 4) probably because of a moderate iron toxicity pressure observed in the pots.

In the field experiment conducted at Korhogo in 1993, with the control (no fertilizer) treatment, the tolerant cultivar, Suakoko 8, outyielded Bouake 189 (Table 5). The effects of different nutrient combination treatments for Suakoko 8 were not clear, because of severe lodging, especially when N was applied. Nutrient application had no clear effect on the iron toxicity score for Suakoko 8. However, the application of P+K with N, and the N+P+K+Zn combination significantly improved the yield of iron-toxicity susceptible Bouake 189, although the application of N alone did not affect the yield or iron toxicity score of either of the two cultivars. The results of the field experiment at Korhogo, where iron toxicity pressure was consistently high, suggested that the role of other nutrients, such as P or K, could be important in increasing the yield of susceptible cultivars in iron-toxic soils. These results also confirm our observations in the pot experiment where the application of P alone or in combination with K and Zn delayed the appearance of iron toxicity symptoms but did not alleviate them.

Plant analysis of Suakoko 8 and Bouake 189 showed no apparent differences in elemental composition with regard to macro- and micro-nutrients (Table 6). Critical limits for deficiency and toxicity (Yoshida 1981; Fageria *et al.* 1991) can only serve as a rough guide but it seems that all nutrient elements, except iron, were adequate for both cultivars. Both iron-tolerant and susceptible cultivars had a high iron content, well above the critical limit for iron toxicity. Suakoko 8 accumulated high amounts of Al, bordering toxic concentrations. The concentrations of Mg, especially in Suakoko 8 plant tops, were bordering deficiency.

It is possible that the application of other nutrients might have increased the capacity of the rice roots to exclude iron (Yoshida 1981; Ottow *et al.* 1991) and this could have increased the yield of the susceptible cultivar. Indeed there was a significant decrease in iron uptake by the two cultivars when other nutrients were applied and this decrease was higher in Bouake 189 (Table 6).

Cultivars with high levels of tolerance to soil stresses such as Fe toxicity are generally traditional types with poor plant structure (De Datta *et al.* 1994). For example, Suakoko 8, an iron-toxicity tolerant cultivar, lodges badly, especially when N is applied. It has been reported that lodging resistance, which is linked to plant height and strength of the culm and rooting is negatively correlated with iron tolerance (De Datta *et al.* 1994). We have observed that the iron-susceptible cultivar, Bouake 189, grows vigorously and at the same time shows extensive symptoms of iron toxicity. On the other hand CK4, an iron-tolerant cultivar, also has high plant vigour but shows very few symptoms of iron toxicity when grown in iron-toxic soils.

The results of this study show that genetic tolerance to iron toxicity can significantly contribute to rice production in iron-toxic soils. Some available cultivars possess a significant degree of tolerance to iron toxicity and can yield > 5 t/ha in iron-toxic soils. These cultivars can be used with advantage to boost rice production in irrigated and lowland rice systems where iron toxicity is one of the major constraints for rice production. However, cultivars tolerant of iron toxicity generally have poor plant structure and there is therefore an urgent need to incorporate the genes responsible for iron-toxicity tolerance from the traditional cultivars to varieties of rice plants in which plant structure and grain quality have already been improved.

There is an interaction between iron toxicity and availability of other nutrients but this interaction is still poorly understood. There is certainly a negative effect of iron toxicity on the availability of nutrients such as P, K and Zn, which could explain why a grain yield response is sometimes obtained by application of these nutrients, especially P. The lack of response to the application of other nutrients in a tolerant cultivar was somewhat confounded by lodging but there was no effect on iron-toxicity score either.

Our results also demonstrated that the application of other nutrients reduced iron uptake in rice tops (Table 6). Additional research needs to be conducted into the relationship between iron toxicity and nutrient supply.

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