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Elemental Composition of the Rice Plant as Affected by Iron Toxicity Under Field Conditions

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ABSTRACT

Iron (Fe) toxicity is a major nutrient disorder affecting the production of wetland rice in the humid zone of West Africa. Little attention has been given to determining the macro- and micronutrient composition of rice plants grown on wetland soils where Fe toxicity is present although results from such study could provide useful information about the involvement of other nutrients in the occurrence of Fe toxicity. A field experiment was conducted in the 1997 dry season (January-May) at an Fe toxic site in Korhogo, Ivory Coast, to determine the elemental composition of Fe tolerant (CK 4) and susceptible (Bouake 189) lowland rice varieties without and with application of nitrogen (N), phosphorus (P), potassium (K), and zinc (Zn). For both Fe-tolerant and susceptible varieties, there were no differences in elemental composition of the whole plant rice tops, sampled at 30 and 60 days after transplanting rice seedlings, except for Fe. All the other nutrient element concentrations were

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adequate. Both Fe-tolerant and susceptible cultivars had a high Fe content, well above the critical limit (300 mg Fe kg^{-1} plant dry wt). These results along with our observations on the elemental composition of rice plant samples collected from several wetland swamp soils with Fe toxicity in West Africa suggest that "real" iron toxicity is a single nutrient (Fe) toxicity and not a multiple nutrient deficiency stress.

INTRODUCTION

Iron toxicity is a major nutrient disorder affecting the production of wetland rice in the humid tropical regions of Asia and Africa. The disorder is a physiological stress caused by high amounts of ferrous Fe mobilized under the reduced conditions of wetland rice. Iron toxicity in wetland rice has been reported from several countries in Asia and West Africa (Ponnamperuma, 1972; Moormann and van Breemen, 1978; Yoshida, 1981; Sahrawat et al., 1996) since its first report in 1955 by Ponnamperuma et al. (1955).

There have been conflicting reports about the involvement of other plant nutrients in the occurrence of and tolerance to iron toxicity in wetland rice. For example, Benckiser et al. (1982, 1984) and Ottow et al. (1983) reported that iron toxicity in wetland rice was caused by multiple nutrient deficiencies of nutrients such as P, K, calcium (Ca), magnesium (Mg), and Zn. Their results were based on the survey of plant and soil samples collected from Fe-toxic sites and greenhouse pot studies. Deficiencies of nutrients such as P, K, Ca, Mg, and manganese (Mn) are known to decrease the Fe-excluding power of rice roots and can thus affect the rice plant's tolerance to Fe toxicity (Yoshida, 1981). Deficiencies of Ca and Mg, and Mn are rarely observed on lowland rice and therefore P and K deficiencies probably deserve special attention. For example, Trolldenier (1973) showed that under low concentration of K, the ability of the rice roots to oxidize Fe(II) to Fe(III) is impaired and this results in higher uptake of iron and increases the probability of Fe toxicity occurrence in rice. Beneficial effect of K application in reducing Fe toxicity in wetland rice was also reported by Yamauchi (1989).

The availability of Zn is reduced under submerged conditions of wetland rice (Ponnamperuma, 1972; Narteh and Sahrawat, 1999) and equally importantly, high concentration of Fe in soil solution may further aggravate Zn availability to wetland rice (Randhawa et al., 1978).

Based on the results of a number of field studies made on Fe-toxic soils in Ivory Coast (Cote d'Ivoire), Sahrawat et al. (1996) suggested that although field application of nutrients such as N, P, K, and Zn reduced Fe toxicity in several Fe-tolerant and Fe-susceptible lowland rice cultivars, plant analysis indicated that these nutrient elements were not deficient. It was concluded that under high concentration of Fe in soil solution, the rice plant's requirements for other nutrients is increased.

TABLE 1. Chemical characteristics of the Ultisol at the experimental site at Korhogo, Ivory Coast, 1997.

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

Little attention has been given to determine the elemental composition of macro- and micronutrients in field-grown rice, although analysis of plants for nutrient elements from field experiments made on well characterized, Fe-toxic sites, could provide further information about the involvement of other nutrients in the occurrence of Fe toxicity in wetland rice. This paper presents the results of a study made on the elemental composition of lowland rice varieties grown on an Fe-toxic soil.

MATERIALS AND METHODS

Plant samples, consisting of whole plant tops, were sampled from a field experiment conducted in the 1997 dry season (January-May) at the Fe-toxic site in Korhogo, Ivory Coast. The Korhogo site is located in the savanna zone and the soil at the site was an Ultisol (Sahrawat et al., 1996).

Some chemical characteristics of the surface (0-0.2 m) soil at the experimental site are in Table 1. For soil analysis, pH was measured by a glass electrode using a soil to water or 1 *M* KCl ratio of 1:2.5. Organic C was determined following the Walkley-Black method (Nelson and Sommers, 1982). Bray 1 extractable P was determined as described by Olsen and Sommers (1982) and DTPA extractable Zn and Fe were determined as described by Lindsay and Norvell (1978). Exchangeable K, Ca, and Mg (Jackson, 1967) and cation exchange capacity (Chapman, 1965) were also determined.

In the field experiment, the plus nutrient treatment received 100 kg N ha^{-1} applied in three split applications. All other nutrients were added as basal applications. Phosphorus was applied at 50 kg P ha^{-1} as triple superphosphate, K was applied at a rate of 80 kg K ha^{-1} as potassium chloride, and Zn was applied at a rate of 10 kg Zn ha^{-1} as zinc sulfate. Iron-tolerant (CK 4) and susceptible (Bouake 189) varieties were grown under irrigated conditions without (0) and with (+NPKZn) fertilizer treatments. Seedlings (3 weeks old) were transplanted to the rice paddies using a spacing of 25x25 cm.

Plants were visually scored for iron toxicity symptoms, using a scale of 1-9 based on the IRRI (International Rice Research Institute) 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).

Plant samples consisting of whole plant tops, were sampled at 30 and 60 days after transplanting. Ten whole plant tops, randomly selected from four replicates, were collected and analyzed for macro- and micronutrient elements using standard methods of plant analysis (Jones et al., 1991). Potassium, Ca, Mg, Fe, Mn, and Zn in the plant digests were determined by atomic absorption spectrophotometry. At harvest of the crop, grain and straw yields were recorded, and grain and straw samples were analyzed for nutrient elements as described above.

RESULTS AND DISCUSSION

The site at Korhogo is a " hot spot" field site for conducting research related to Fe toxicity in wetland rice, and the lowland rice crop grown on the site experiences a high degree of Fe toxicity stress (Sahrawat et al., 1996). The physiological stress due to Fe toxicity is far greater in dry season than in the wet season. The higher stress in the dry season is caused by higher uptake of Fe by rice plants. Relatively higher ambient temperature in the dry season mobilizes greater amounts of Fe in soil solution and this coupled with high evapotranspiration, results in higher uptake of Fe from Fe-toxic soils (Sahrawat and Singh, 1998).

During the growing season, typical Fe toxicity symptoms were observed on the plants which initially 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 and with increased Fe toxicity, the entire leaf appeared purplish-brown (Sahrawat et al., 1996). Iron toxicity symptoms on the lower leaves of rice plants first appeared at about 3 weeks after transplanting and with increasing Fe toxicity stress the bronzing symptoms spread to the upper leaves. Maximum Fe toxicity symptoms were observed at about 9 weeks after transplanting.

There were differences in the growth and biomass produced by the two rice varieties. The Fe-tolerant variety, CK 4 out-yielded Fe-susceptible Bouake 189 both without and with nutrient treatments. Based on the visual symptoms on rice foliage indicated by Fe toxicity scores at 60 days after transplanting, Fe toxicity stress was high. Application of nutrients caused non-significant increases in grain yields of the two varieties and straw yield of Bouake 189. The application of nutrients, however, significantly increased straw yield of CK 4 (Table 2). Nutrient

TABLE 2. Iron toxicity score (ITS) of rice plants at 60 days after transplanting, and grain and straw yields at harvest of iron-tolerant (CK 4) and susceptible (Bouake 189) lowland rice varieties without and with the application of nutrients on an iron-toxic soil at Korhogo, Ivory Coast, in 1997.

Treatment	CK 4			Bouake 189		
	Grain	Straw ($t\ ha^{-1}$)	ITS	Grain	Straw ($t\ ha^{-1}$)	ITS
No nutrients	3.88	4.38	5	2.23	2.63	7
NPKZn	4.16	5.74	3	2.34	3.65	7
LSD (0.05)	1.40	0.97		2.03	1.18	

application also reduced Fe toxicity score in the Fe tolerant CK 4, but not in Fe-susceptible Bouake 189. The results indicated that Fe toxicity has relatively greater detrimental effect on rice grain production (Yoshida, 1981). It is important to note that CK 4 and Bouake 189 are high yielding lowland rice varieties and they can produce grain yields ranging from 6 to 8 t ha under irrigated conditions on soils where Fe toxicity is absent. Our results also show that Fe toxicity can cause an apparent grain yield loss of 12 to 49%.

The elemental composition of rice plants of the two lowland rice varieties at 30 and 60 days after transplanting of the rice seedlings are given in Table 3. Plant analysis of CK 4 (Fe-tolerant variety) and Bouake 189 (Fe-susceptible variety) showed no apparent differences in elemental composition with regard to macro- and micronutrients. Critical limits for deficiency and toxicity (Fageria, 1991; Yoshida, 1981) can only serve as a rough guide for interpreting the results. It seems, however, from our results that all nutrient elements, except Fe, were adequate for both rice varieties. Both Fe-tolerant and Fe-susceptible varieties had a high Fe content at the two sampling times, well above the critical limit (300 mg Fe kg^{-1} dry matter) for the occurrence of Fe toxicity in the rice plant.

The concentration of nutrient elements with the exception of Mn, decreased with time and there were no clear differences between the varieties except that at 30 days after transplanting , CK 4 plant samples contained higher amounts of N, Ca, and Mg, but lower amount of K than Bouake 189, and these differences were not observed at 60 days after transplanting. Plant samples contained higher amounts of Fe and the concentration was increased with the application of nutrients at 30 days after transplanting. This trend was, however, not observed at 60 days after transplanting (Table 3). This is not unexpected because it is known that young plant tissue has higher capacity to accumulate nutrients (Walker and Peck, 1972). The lower concentration of the nutrients at 60 days after transplanting was caused by growth and the dilution effects. The deficiencies of Ca and Mg are rare in

TABLE 3. Nutrient content (mg kg^{-1}) in plant tops of iron-tolerant (CK 4) and susceptible (Bouake 189) rice varieties without (0) and with (+NPKZn) treatment at 30 and 60 days after transplanting (DAT) at Korhogo, Ivory Coast, in 1997.

Nutrient	At 30 DAT				At 60 DAT			
	CK 4		Bouake 189		CK 4		Bouake 189	
element	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

irrigated lowland rice (Yoshida, 1981; Sahrawat et al., 1996) perhaps with the exception of lowland rice grown on *acid sulfate soils in mangrove swamps (Konsten* et al., 1994; Sylla, 1994). The results of this study showed that Ca and Mg contents in rice plants remained in the adequate concentration range.

At harvest, the concentration of Fe in grain was lower in CK 4 than Bouake 189, but reverse was the case for Fe content in the straw. Application of nutrients increased Fe contents in grain and straw of CK 4. Iron uptake in grain and straw was higher in CK 4 than Bouake 189 both without and with application of plant nutrients. Higher uptake of Fe by CK 4 compared to Bouake 189 was as a result of higher yields produced by CK 4 than Bouake 189. The increase in Fe content as a result of nutrient application was larger in straw than in grain of both CK 4 and Bouake 189. Application of nutrients also increased uptake of Fe in biomass of the two varieties (Table 4).

Our observations on the composition of rice plants growing on soils without iron toxicity, but under similar experimental conditions, showed that they differed only in the content of Fe. Iron content in the plant samples generally varied from 100 to 320 mg kg^{-1} dry wt and the contents were far lower than those found in the plants grown on the Fe-toxic soils.

The results of this study on the rice plant composition of Fe-tolerant and susceptible varieties suggest that iron toxicity observed in the field at Korhogo site is caused by high content of Fe in the plant and not by the deficiency of other nutrients. As noted before, the site in Korhogo offers high Fe toxicity stress and severe symptoms of the disorder were observed on the rice plant foliage. Research on the role of other nutrients in iron toxicity has shown that the application of other nutrients especially P, K, and Zn can reduce Fe toxicity in wetland rice grown

TABLE 4. Iron content and uptake in iron-tolerant (CK 4) and susceptible (Bouake 189) rice varieties at harvest of the crop without and with application of nutrients at the iron toxic site in Korhogo, Ivory Coast, in 1997.

	CK 4			Bouake 189		
Treatment	Grain	Straw	Total	Grain	Straw	Total
	Iron content (mg kg^{-1} of dry matter)					
No nutrients	234	1413		364	1768	
NPKZn	288	1469		357	1865	
	Iron uptake (kg ha^{-1})					
No nutrients	0.91	6.20	7.11	0.81	4.60	5.41
NPKZn	1.20	8.40	9.60	0.84	6.80	7.64

on soils where Fe toxicity is present. It appears that plant requirements for these nutrients is increased in soils where Fe concentration in soil solution is high. Other nutrients are involved in overcoming their physiological deficiencies induced by Fe toxicity. Other plant nutrients also affect the uptake and accumulation of Fe in plant tissue through their influence on rice plant rhizosphere and other secondary effects (Sahrawat, 1999).

We have observed that the same degree of Fe toxicity stress as observed in the field, cannot be created in greenhouse pots using the same Fe-toxic soil. The main reasons for this seem limited volume of soil in the pots for mobilizing Fe in solution and the diffusion of air especially, in smaller pots or containers, has greater effect in precipitating the soluble Fe into insoluble at the flood water-oxygenated soil phase. It is important to note that ferric-ferrous Fe reactions that control the amount of soluble Fe available in the growing medium are delicately poised in pots with limited volume. The growth and mineral nutrition of the rice plant with regards to nutrients such as Fe, whose solubilities are influenced by the redox reactions, are likely to be differentially influenced under greenhouse pot and field conditions.

More importantly, the results of this study and our observations on the elemental composition of rice plant samples collected from several field sites in West Africa, suggest that "real" Fe toxicity in lowland rice is a single nutrient toxicity and not a multiple-nutrient deficiency.

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