Devices of Rice Roots to Tolerate High Iron Concentration in Growth Media

By TOSHIAKI TADANO

Faculty of Agriculture, Hokkaido University

Introduction

Iron concentration in a soil solution increases significantly when soil is kept under submerged condition. Thus, lowland rice frequently suffers from iron toxicity which is very seldom found in upland crops.

Iron toxicity symptoms of rice plants are characterized by the development of brown spots starting from the tips of the lower leaves, the spots spread over the leaves, then even on the upper leaves, and eventually the lower leaves begin to turn gray and die.

The symptoms are, however, different significantly with age of plants and among varieties. Due to this reason, it is frequently difficult to identify iron toxicity by the symptoms[1].

The cases of iron toxicity of rice plants in cultivator's fields are that on acid sulfate soils[2,3], "bronzing" in Sri Lanka, formerly Ceylon[1,3,4] and "Akagare type I" in Japan[3,5]. "Akiochi" in Korea is also suspected to be associated with iron toxicity[6].

However, there are instances that the rice plant is kept normal even though the soil solution is high in iron content[7,8], and there is no simple relation between the iron concentration in the growth media and the condition of the rice plant. Thus, it appears that the susceptibility of rice plants to iron toxicity is influenced by physiological status of the plants.

It was reported that iron absorption by the roots from a culture solution containing a high level of iron was accelerated considerably when the roots were trimmed at the tips[1] or damaged by H_2S[9]. These phenomena suggest that the healthy rice roots have devices to protect the plant against high iron concentration in the growth media.

Devices of roots to tolerate high iron concentration

Rice roots have three devices to escape from iron toxicity even if iron concentration in the growth media is high. These are the powers of roots (a) to make iron concentration in the growth media lower, (b) to interrupt the iron which reaches to the root surface from entering into the root (iron excluding power), and (c) to interrupt the iron which entered into the root from translocating to the shoot (iron retaining power). Followings are the evidences of the existence of these devices.

Power to lower iron concentration in growth media

Graded levels of potassium were applied to pots containing soil which is moderately low in potassium-supplying power and rice plants were planted to them. Extra pots were prepared in which no plants were grown[10].

Soil solution pH decreased during the active growth of the plants, reached a minimum, and then increased at later stages of growth (Fig. 1). Without plants, however, pH continued to increase.

Iron concentration in the soil solution increased rapidly after submergence, reached

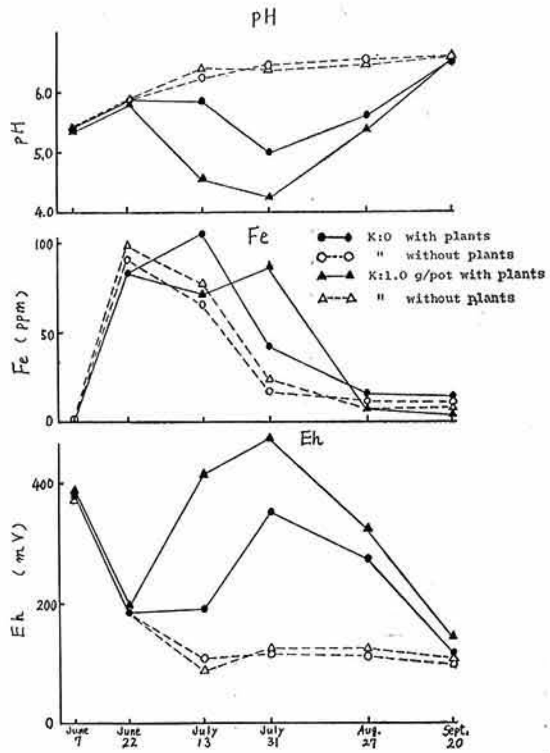

Fig. 1. Changes of pH, iron concentration and Eh in the soil solution of Bibai peat soil by the growth of the rice plants with and without potassium application

a maximum, and then decreased. The difference between with and without plants was not apparent. Without plants, Eh decreased for about a month after submergence, and then kept constant.

On the other hand, with plants, Eh started to increase from two weeks after transplanting, reached a peak, and then decreased again. The increase of Eh during the growth was more prominent with potassium application.

These results demonstrate that rice roots have a power to increase Eh of the soil solution, which causes a decrease of the iron concentration in the soil solution. It was reported that rice roots secrete oxygen to the growth media and oxidize ferrous iron to ferric[11].

In this experiment, however, no difference was observed in the actual iron concentration between with and without plants because pH was lower with plants. The iron concentration could have been much higher with plants if Eh as low as that without plants.

Iron excluding power

Rice plants were transferred to culture solutions containing graded levels of Fe^{++}, kept for 20 hours in a greenhouse, and then the concentrations of Fe^{++} and Fe^{+++} in the remaining culture solution were determined[12]. At lower levels below 10 ppm Fe, Fe^{++} concentration in the culture solution decreased, whereas at higher levels than 50 ppm Fe it increased (Table 1).

Table 1. Ferric and ferrous iron concentration in the remaining culture solution where rice plants are subjected to graded levels of ferrous iron for 20 hours

Initial concentration (ppm Fe^{++})	Concentration in remaining solution (ppm)	
	Fe^{+++}	Fe^{++}
1	0	0.7
10	0	9.5
50	0	53
100	0	109
300	0.3	318

The decrease in Fe^{++} concentration at lower levels below 10 ppm Fe and the increase at higher levels than 50 ppm Fe were confirmed with many conducted experiments. These data indicate that iron is selectively absorbed or excluded relative to water by the roots when the iron level is low or high.

Iron absorption by the rice plant from a culture solution containing 300 ppm Fe increased when the respiration of roots was retarded by various respiratory inhibitors[13] (Table 2). The iron excluding power (see the foot note of Table 2) of the healthy plants was 97 per cent. This means that 87 per cent of the total amount of iron which reach to the root surface along with the water absorbed by the plant was "not absorbed", in other word "excluded". With

Table 2. Effecte of respiratory inhibitors on the iron-excluding power of rice roots (300 ppm Fe, labelled with ^{59}Fe)

Inhibitors	Concentration of inhibitor (M)	Respiratory rate (μl O_2 per 100 mg dry roots/hr)	Water uptake (ml per plant)	Fe uptake (mg per plant)	Iron-excluding* power (%)
None	—	39.3	49	1.93	87
KCN	10^{-4}	26.6	36	3.34	69
	10^{-3}	2.6	30	5.73	36
NaN_3	10^{-4}	5.2	23	4.51	37
	10^{-3}	1.1	23	5.23	24
DNP	10^{-5}	35.5	51	5.45	64
	10^{-4}	2.8	27	5.69	30

* Iron-excluding power (%)$=(a-b)/a\times 100$, where a is the amount of Fe considered to be contained in the amount of water absorbed by the plant (mg) and b is the amount of Fe actually absorbed by the plant (mg)

Table 3. Effect of NaCl on the absorption and the translocation of iron (300 ppm Fe, labelled with ^{59}Fe absorption period: 24 hours)

Concentration of NaCl (ppm Na)	Fe content (ppm)		Fe uptake (mg/plant)	Water uptake (ml/plant)	Transloca-tion of Fe (%)	Iron ⊖ excluding* power (%)
	Shoots	Roots				
0	166	7,180	2.36	53	8.7	85
200	228	6,580	2.08	49	13.0	86
500	241	6,030	1.93	40	14.4	84
1,000	315	5,880	1.86	35	19.5	82

* Same as in Table 2

respiratory inhibitors the iron excluding power was weakened remarkably.

From these data it can be concluded that the rice roots have iron excluding power. The power is operated by the respiration only when the iron concentration in the growth media is high.

Iron-retaining power

Some part of the iron entered into the roots translocates to the shoot and the other part is retained by the roots. The iron-retaining power of the roots can be expressed by the translocation percentage which is the per cent of amount of iron translocated to the shoot in the basis of the total amount of iron absorbed by the plant.

Water cultured rice plants were transferred to culture solutions containing 300 ppm Fe and graded levels of NaCl, and absorption of water and iron was determined[14].

With an increase of NaCl level, the amount of water absorbed by the plant decreased, iron content of the shoots increased, that of the roots decreased, the total amount of iron absorbed by the plant decreased, the translocation percentage of iron increased, and the iron-excluding power was kept constant (Table 3).

Table 4. Effect of 1,000 ppm Na-NaCl on the Fe^{++} oxidizing power of the excised rice roots

Treatment	Increase of Fe^{+++} content (mg Fe^{+++}/4 g fresh roots)
−NaCl	0.97
+NaCl	0.32

* Four grams of fresh excised roots were added to 450 ml of culture solution containing 100 ppm Fe^{++} with and without 1,000 ppm Na-NaCl and kept for 3 houres with aeration at 25°C. Fe^{+++} content increase of the roots during the treatment was determined

On the other hand, the power of the excised roots to oxidize ferrous iron absorbed by the roots to ferric was inhibited by 1000 ppm Na-NaCl (Table 4).

These results indicate that the increase of iron content of the shoots by a high level of NaCl is not due to a decrease of the iron-excluding power of the roots but to a decrease of the iron-retaining power of the roots which may be mainly derived from the Fe^{++} oxidizing power of the roots.

Factors affecting devices to tolerate high iron concentrations

Age of the plant

The iron-excluding power of the rice plants grown with a standard culture solution was measured at successive growth stages[15]. The iron-excluding power of the foots was low at early growth stages, increased till the flowing stage, and then decreased gradually (Table 5).

Table 5. Iron-excluding of rice plants at different growth stages
(Fe concentration: 100 ppm, 24 hours)

Age of plants (days after transplanting)	Iron-excluding power (%)
5	49
15	73
55*	75
70	60
90	55

* Flowering stage

In a separate experiment, the rice plants at various growth stages were subjected to a culture solution containing 300 ppm Fe for two days, and the amounts of iron absorbed during the treatment in the roots and shoots were measured[15]. The results in Table 6 demonstrate that the iron-retaining power of the roots decreases with the growth.

By the combination of the changes of the iron-excluding power and the iron-retaining power with the age of plants, the rice plant is more susceptible to iron toxicity at early and at later growth stages, and more resistant at middle growth stages. Of course, when the rice plants are subjected to a high level of iron for a prolonged period, iron accumulates in the shoots gradually with the growth, and the plants have more chances to gradually with the growth, and the plants have more chances to suffer from iron toxicity.

Table 6. Translaction of iron from the roots to the shoots in the rice plants at different growth stages

Age of plants (days after transplanting)	Translocation percentage of Fe	Fe content (ppm) shoots/roots $\times 10^{-2}$
5	5.5	2.2
25	5.1	2.0
45	13.3	3.2
60	14.9	2.8
80	24.9	4.0
95	28.7	4.3

* Fe concentration in a culture solution was 300 ppm, ^{59}Fe was labelled, 2 days

Nutritional status of the plant

The iron-excluding power and the iron-retaining power of the rice plants deficient in various nutrient elements were determined with 100 ppm Fe solution[12]. The iron-excluding power was lower in the plants deficient in calcium, magnesium, phosphorus and manganese, especially in potassium, than the normal or nitrogen-deficient plants (Table 7).

Translocation percentage was smaller in the plants deficient in nitrogen, but larger in the plants deficient in magnesium, manganese, potassium and calcium than the normal plants.

Combination of the influence of nutrient deficiency to the iron excluding and retaining powers resulted in a high iron content of the shoots in the plants deficient in calcium, magnesium, manganese and phosphorus, especially in potassium than the normal plants. Thus, it can be concluded that rice

Table 7. Absorption and translocation of iron and iron-excluding power of rice plants deficients in various nutritional elements (100 ppm Fe)

Status of plant	Fe content (ppm)			Translocation percentage of iron	Iron-excluding power (%)
	upper leaves	lower leaves	culm		
Complete	423	732	390	3.5	60
−N	398	830	495	2.5	60
−P	458	864	407	3.7	30
−K	617	983	808	4.5	20
−Ca	544	910	413	4.6	22
−Mg	602	998	480	5.5	27
−Mn	601	826	570	5.4	38

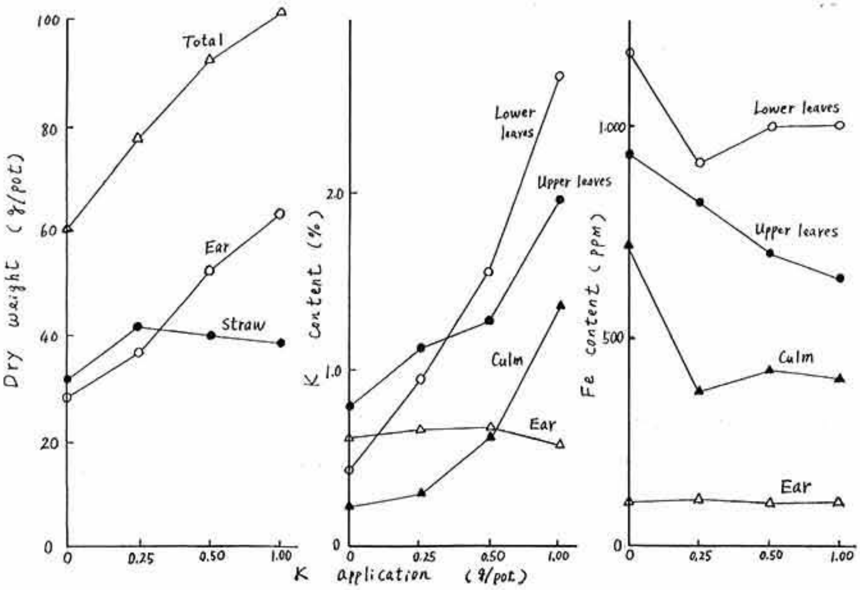

Fig. 2. Effect of potassium application on dry weight and content of potassium and iron of the rice plants grown in Bibai peat soil

plants deficient in potassium, calcium, magnesiuum, manganese and phosphorus are more susceptible to iron toxicity than normal plants.

Rice plants deficient in potassium are most susceptible to iron toxicity due to weakness of the powers of the roots to lower the iron concentration in the growth media, to exclude iron and also to retard the translocation.

In fact, a soil culture experiment showed that the plants grown without potassium application were lower in potassium content, higher in iron content and more severe in the toxicity symptoms than those grown with potassium application (Fig. 2).

Methods to prevent iron toxicity

There are two categories of the method to prevent iron toxicity in cultivator's fields.

(1) Methods to maintain iron concentration in low soil solution: Adjustment of pH; drainage or intermittent irrigation; and adequate management of organic substances in the soil.

(2) Methods to improve the protecting devices of the rice plant against high concentration of iron in the soil solution: Use of fertilizers containing no sulfur and good

aeration of the soil to avoid accumulation of hydrogen sulfide, organic acids, etc. in the soil, which inhibit the respiratory activity of the plants; application of potassium, magnesium, lime, manganese or phosphorus when the soil is low in supplying power of these elements; in soil high in sodium chloride as reclaimed land from the sea, removal of sodium chloride by heavy leaching is a prerequisite.

Acknowledgment

The author is greatly indebted to Dr. A. Tanaka, Professor, Faculty of Agriculture, Hokkaido University, for his valuable suggestions in the course of this study.

References

1) Tanaka, A., Loe, R. & Navasero, S. A.: Some mechanisms involved in the development of iron toxicity symptoms in the rice plant. *Soil Sci. and Plant Nutr.*, **12**, 158–164 (1966).
2) Tanaka, A. & Navasero, S. A.: Growth of the rice plant on acid sulfate soils. *Soil Sci. and Plant Nutr.* 12, 107–114 (1966).
3) Tanaka, A. & Yoshida, S.: Nutritional disorders of the rice plant in Asia. *Int. Rice Res. Inst. Tech. Bull.*, **10** (1970).
4) Ponnamperuma, F. N., Bradfield, D. & Peach, M.: Physiological disease of rice attributable to iron toxicity. *Nature*, **175**, 265–266 (1955).
5) Baba, I. & Tajima, K.: Studies on the nutrition of the rice plant in relation to the occurrence of the so-called "Akagare" disease. VI. Changes in the growth, nutrient absorption, and metabolism in the plant as influenced by the excessive supply of ferrous iron. *Proc. Crop Sci. Soc. Japan*, **29**, 47–50 (1960).
6) Park, Y. D. & Tanaka, A.: Studies of the rice plant on an "Akiochi" soil in Korea. *Soil Sci. and Plant Nutr.*, **14**, 27–34 (1968).
7) Takagi, S.: Studies on the inhibiting factors of the rice plant growth in the muck paddy soil under pot experiment condition. *Bull. Inst. Agr. Res., Tohoku Univ.*, **10**, 13–28 (1958) [In Japanese, English summary].
8) De, P. K. & Mandal, L. N.: Physiological diseases of rice. *Soil Sci.*, 84, 367–376 (1957).
9) Tanaka, A., Mulleriyawa, R. P. & Yasu, T.: Possibility of hydrogen sulfide induced iron toxicity of the rice plant. *Soil Sci. and Plant Nutr.*, 14, 1–6 (1968).
10) Tadano, T., & Tanaka, A.: Studies on the iron nutrition of rice plants (3). Iron absorption affected by potassium status of the plant. *J. Sci. Soil and Manure, Japan*, 41, 142–148 (1970) [In Japanese, English summary].
11) Kumada, K.: Investigation on the rhizosphere of rice seedling. (1) On the microscopic structure of the rhizosphere and oxidative power of root. *J. Sci. Soil and Manure, Japan*, **10**, 119–124 (1949) [In Japanese, English summary].
12) Tadano, T.: Studies on the iron nutrition of rice plants. (4) Excess iron absorption as affected by nutritional status of the plant. *J. Sci. Soil and Manure, Japan*, 41, 498–501 (1970) [In Japanese, English summary].
13) Tanaka, A., & Tadano, T.: Studies on the iron nutrition of rice plants (2) Iron excluding capacity of the rice roots. *J. Sci. Soil and Manure, Japan*, 40, 469–472 (1969). [In Japanese, English summary].
14) Tadano, T.: Unpublished data.
15) Tadano, T.: Studies on the iron nutrition of rice plants (5) Changes of the susceptibility to iron toxicity during growth. *J. Sci. Soil and Manure, Japan* [In Japanese, English summary] (In press).